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LANDFILL RESEARCH AT THE BOONE COUNTY FIELD SITE

Final Report

by

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Purchase Order No. C3016NASX

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16. ABSTRACT

Sanitary landfills presently play a significant role in the disposal of solid wastes, and they will probably continue to do so in many areas because of their economic advantages over other methods. However, justifiable concern exists about the environmental effects of sanitary landfills. The research project described here was undertaken to provide a better understanding of the processes that occur within a sanitary landfill and the related environmental effects.

The initial field-scale test cell was completed in June 1971 and was monitored for temperature, gas composition, settlement, and leachate quantity and characteristics until closure in September 1980. Four additional cells (2A, 2B, 2C 2D) were constructed during August 1972. One of these was field-scale (2D), and the others were small-scale cells that simulated the large cell for the purpose of performance comparison. Water input to these cells was controlled, and all cells were monitored for temperature, gas composition, settlement, and leachate quantity and characteristics. This report presents the results of the analysis of the data collected from the batch-type cells during the nine year monitoring period.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research - a most vital communications link between the researcher and the user community.

The information presented here was gathered from long-term monitoring of five sanitary landfill cells (two field-scale and three small-scale). The cells were constructed to provide an understanding of sanitary landfill behavior, the potential effects on the environment, and the validity of conducting this research with small-scale cells.

Francis T. Mayo
Director
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Laboratory

ABSTRACT

Sanitary landfills presently play a significant role in the disposal of solid wastes, and they will probably continue to do so in many areas because of their economic advantages over other methods. However, justifiable concern exists about the environmental effects of sanitary landfills. The research project described here was undertaken to provide a better understanding of the processes that occur within a sanitary landfill and the related environmental effects.

The initial field-scale test cell was completed in June 1971 and was monitored for temperature, gas composition, settlement, and leachate quantity and characteristics until closure in September 1980. Four additional cells (2A, 2B, 2C and 2D) were constructed during August 1972. One of these was field-scale (2D), and the others were small-scale cells that simulated the large cell for the purpose of performance comparison. Water input to these cells was controlled, and all cells were monitored for temperature, gas composition, settlement, and leachate quantity and characteristics. This report presents the results of the analysis of the data collected from the batch-type cells during the nine year monitoring period.

This report was submitted in fulfillment of Purchase Order No. C3016NASX by Regional Services Corp., Inc., under the sponsorship of the U.S. Environmental Protection Agency.

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SECTION I

INTRODUCTION

The Boone County Field Site consisted of a four hectare tract of land leased from a private disposal facility located 8 km west of the City of Walton, Kentucky, in Boone County. Available facilities at the site included an office trailer, a pole barn, and a truck scale. Equipment included an industrial tractor with a backhoe and front-end loader, a portable power soil auger, a trailer mounted water tank, and miscellaneous tools. An instrumentation shed was placed near the test cells and a weather station was erected at the site.

The geologic setting of the site is the northwestern section of the physiographic Interior Low Plateau Province. Elevations at the research site range between 213 and 244 m above sea level. Surficial soils at the site are predominantly a lean clay, classified by the USDA as Nicholson silt loam. Rubbly limestone mixed with thin beds of soft calcareous shales of the Fairview formation underlie the shallow soil. The mean annual precipitation in the area is 927 mm. Monthly normal mean temperatures range from 0 ^{o}C in January to 24.4 ^{o}C in July.

Five municipal waste test cells were constructed during 1971 and 1972. Two were field-scale and three were identical small-scale cells constructed for performance comparisons. The research was concluded and the site closed in September 1980.

The primary objectives of test cells 1, 2A, 2B, 2C, and 2D included:

(1) Analyze the amount and characteristics of leachate.

(2) Analyze the composition of gases present in the cells.

(3) Analyze temperature conditions and compare these temperatures to the conditions existing in the surrounding soil.

(4) Evaluate settlement of the research cells.

(5) Evaluate a silty clay soil as a liner for leachate control.

(6) Evaluate the behavior of a field-scale test cell, 2D, as compared to similarly constructed small-scale test cells, 2A, 2B and 2C.

SECTION II

SUMMARY AND CONCLUSION

Five sanitary landfill test cells containing municipal solid waste were constructed at the Boone County Field Site during 1971 and 1972. Two of the cells, 1 and 2D, were constructed similar to normal landfill cells and contained 286,000 and 72,450 kg of dry refuse respectively. The other three cells, 2A, 2B and 2C, were small-scale, containing approximately 2,100 kg of dry refuse each. Their primary purpose was to evaluate performance variations among similarly constructed cells and to compare the behavior of the small-scale systems to the larger cell 2D. All cells were monitored for leachate quantity and characteristics, gas composition, temperature, and settlement until closure in August 1980.

Until mid-February 1979 leachate collected from cell 1 averaged 27.5% of precipitation. The 1.07 million liters of leachate produced during that period exceeded by only 6% the quantity the water balance method[1] predicted when using actual precipitation and temperature values. If average yearly weather values had been used the difference would have been 33% greater leachate generation observed than predicted. This demonstrates the need for analyzing extreme as well as average weather conditions when using the water balance method as a design tool.

Leachate collected in a drainpipe beneath a soil liner in the base of cell 1 was less than 1% of total leachate flow. The hydraulic conductivity of this silty clay soil decreased by 2-3 orders of magnitude during the life of the project. Leachate concentration reductions were very high during the first half of the project. Even after 9 years iron and COD values were only 50% of the values of the leachate that had not passed through the soil liner. Total solids attenuation averaged 31% over the project. Desorption from the soil of hardness, chloride, calcium, and sulfate occurred during the later part of the study. A complete evaluation of the efficiency of the soil liner in collecting and attenuating leachate could not be performed due to interference from an underlying synthetic liner, variable soil thickness, and a small hole discovered in the soil liner during close-out.

Leachate quantities collected from two of the small-scale cells varied by only 5%. Very little leachate was collected from cell 2C possibly due to a leak in the steel pipe containing the refuse. Cumulative leachate collected from the field-scale cell 2D exceeded precipitation by 53%. The most likely cause was leakage through the sides of the synthetic liner that had been placed in the excavation to contain leachate. Refuse moisture holding capacities of all the cells averaged about 55% moisture on a wet weight basis.

Leachate concentrations generally peaked within a few months of the time period during which field capacity was being achieved. Concentrations of those metals listed in the EPA primary drinking water standards were commonly exceeded in the leachate samples, particularly cadmium, chromium, lead, mercury, and selenium. The typical leachate concentration trend for many of the parameters was the peak at field capacity followed by a slow decline throughout the remainder of the study. Individual leachate sample concentrations showed no dilution effects during periods of high flow.

Long term leachate concentration trends for comparing cell performance were more cumulative leachate volume than time related. The relatively consistent pattern of concentration histories were adequately described with a simple exponential equation developed by considering the cell as a well-mixed reactor. While such an equation was found to be useful in describing leachate characteristics over the 9 year period of the experiment, it's use for long term predictions is uncertain. This uncertainty is exemplified by the findings that total chloride remaining in samples of 9 year old refuse were 70 times greater than leachable chloride predicted by the equation. This finding is not conclusive as all chloride remaining in the refuse may not be leachable. Therefore, to describe the complete leaching process, studies will have to be conducted well beyond the amount of leachate per unit of dry refuse reached in this research program. It is reasonable to assume that concentrations of most constituents will generally continue to follow the trends observed in this study.

Gas analyses showed rapid depletion of oxygen within the cells and a characteristic carbon dioxide bloom. Methane production started in the large cells during the period field capacity was being achieved. Methane was not detected in the small cells in the same concentrations as in the larger ones until approximately 2 years later. Leachate pH did not vary sufficiently during the study to indicate any correlation with methane content. The peak methane concentration recorded was 65% in cell 1. Gas concentrations in the soil around cell 1 ranged as high as 45% methane and 31% carbon dioxide by volume 6.1 meters from the cell. The maximum extent of gas migration was not measured.

Temperatures varied little between the cells. Time lags to annual highs and lows were noted from the top to the base of cells and between soil and refuse peak temperatures. Lower annual temperatures were recorded in the soil than in the refuse. Settlement ranged from 15.2-17.1% of refuse depth in the small cells. Settlement recorded over the surface of 2D was less, averaging 10.6%, probably due to the greater initial refuse density. Estimated total settlement in cell 1 was 12% of refuse depth.

Leachate samples from cell 1 were used for bioassays during 1972. The 96 hour LC 50 was 2.5 and 2.1% for two series of tests on fathead minnows. Microbiologic studies of leachate and waste samples indicated that significant levels of fecal-indicators had continued to survive and reproduce for nine years. Pathogens were also identified in waste samples from cell 1 at closure even though innoculated bags containing poliovirus type 1 and Salmonella derby indicated inactivation within 10 days of the initial construction of cell 1.

Only minor differences in temperature, gas composition and settlement were noted when comparing the performance of the small-scale cells. Graphical comparison of leachate weighted mean concentrations and mass removals indicated good performance similarities. However, statistical evaluation indicated similarity between 2A and 2B leachate at the .05 level of significance for only 3 of 12 parameters. This indicates that while generally similar performance was apparent, there was a sufficient difference between the leachate characteristics during the term of this study that it cannot be concluded that identically constructed and operated cells will perform similarly.

A 45% greater initial in-place wet refuse density in 2D than in the small cells and the much greater volume of leachate collected precluded comparison of performance between the different sized cells. Differences in settlement, gas composition with time, peak leachate concentrations, and mass removals were all apparent in the comparison of the cell data. While it cannot be concluded that 2D would have performed differently if the refuse density and leachate volume had been the same, these operational problems are only minor compared to the range of conditions which may be encountered in a field situation. Therefore, it is doubtful that small-scale batch type cells can provide accurate predictions of sanitary landfill behavior, however, they may be useful in describing performance ranges.

SECTION III

RECOMMENDATIONS

Long term monitoring of five municipal waste test cells at the Boone County Field Site has provided significant information on the performance of batch type refuse test cells. While comparison for similarity of the leachate characteristics from different cells was inconclusive, the results were definitive enough to indicate that there is likely to be substantial differences in the performance of large and small-scale cells, and that procedures used to construct and operate identical cells were not adequate to produce replicate results.

To produce further practical applications from this type of work it is suggested that future research efforts emphasize:

1. Actual sanitary landfill performance over a long term or until stable conditions are reached.

2. Comparison of these results with those from similar studies to determine what range of performance trends might be expected.

3. Determining optimal water input rates to achieve rapid refuse and leachate stabilization.

SECTION IV

CONSTRUCTION OF TEST CELLS

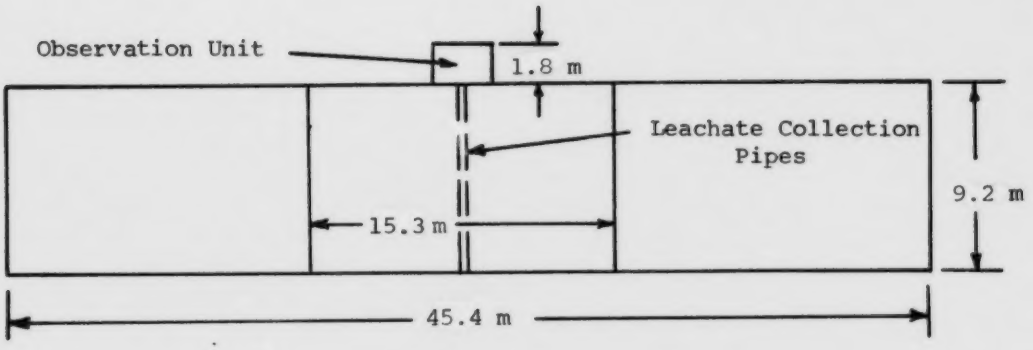
Test Cell #1

Test cell #1 consisted of a 45.4 m long by 9.2 m wide trench. The cell was excavated with vertical side walls and ramps on both ends sloping approximately 1:7. The middle 15.3 m of the trench was sloped approximately 7 percent to the transverse center line as shown in Figure 1. Adjacent to the west side wall of the excavation, an observation unit was constructed for the collection of water samples. Fractured limestone was encountered in the base of the excavation so an additional .18 m of soil and stone were removed below grade and replaced with the lean clay from on-site. This soil was compacted to a wet density of 2035 kg/m^3 at 24.2% moisture on a dry weight basis.

After backfilling, a .76 mm synthetic liner (Hypalon), 9.2 m wide by 15.3 m long, was centered on the base of the cell. This functioned as a sealer to prevent any leachate from migrating below the cell. It was felt that the 1:7 slopes at the ends of the cell would be steep enough to encourage water to flow down the ramps onto the liner without any appreciable seepage loss.

Directly above the liner, as shown in Figures 1 and 2, a 7.6 cm collection pipe was installed along the transverse center line. Slots .95 cm wide halfway through the pipe were cut every 4.72 cm of length on alternate sides. Above this pipe and the synthetic liner, a 45.7 cm thick soil liner was placed and compacted to a wet density of 1915 kg/m^3 at 21.2 percent moisture on a dry basis. Soil characteristics are shown in Table 1. Constant head permeability tests on this soil gave a permeability of 1.64×10^{-5} cm/sec at a dry density of 1584 kg/m^3 under a head of .42 kg/cm^2.

A second slotted collection pipe was installed within the soil liner as shown in Figure 2. A .15 mm thick low density polyethylene liner strip was placed beneath this pipe to prevent leachate from shortcircuiting to the lower pipe. The effective width of this liner was 1.2 m, centered on the collection pipe. Both pipes drained into the observation unit for sample collection. The area around both pipes was backfilled with a silica gravel meeting gradation requirements as a filter. The gravel was limestone-free to eliminate any undesirable chemical reactions. As shown in Table 2, the only material in this silica gravel that might have contributed to the leachate was iron from sandstone and weathered particles in the gravel.



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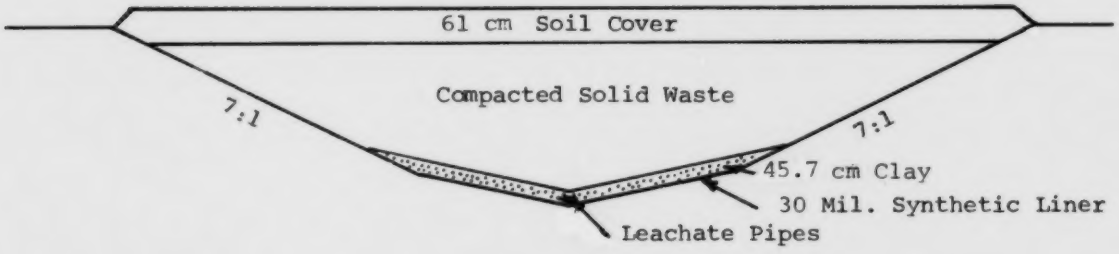
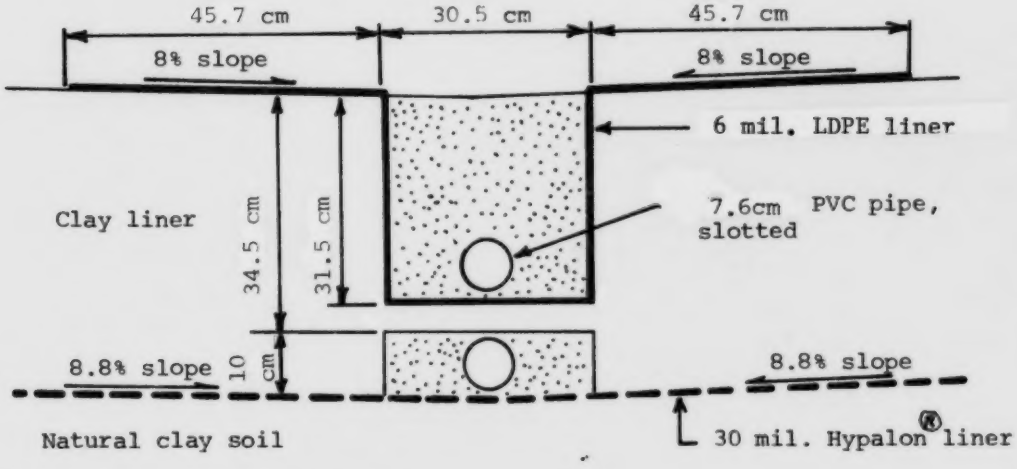


SECTION



DRAIN PIPES

Figures 1 and 2. Cell 1 design and leachate collection pipes.

TABLE 1. SOIL COVER AND SOIL LINER CLASSIFICATION TEST DATA

Sample Source	Mechanical Analysis[a]				Specific Gravity	Atterberg Limits[b]			Classification[c]	Maximum Dry Density[d]
	Gravel	Sand	Silt	Clay		Liquid Limit	Plastic Limit	Plasticity Index		
Cover Material	0	6	66	28	2.68	36.5	23.8	12.7	CL	
Soil Liner	0	5	59	36	2.74	44.0	22.7	21.3	CL	103.3
						83.0	28.0	55.0	CH	
						79.0	29.0	50.0	CH	

a. percent by weight

b. percent

c. Unified Soil Classification System

d. lbs/ft^3

TABLE 2. PETROGRAPHIC ANALYSIS OF SILICA SAND AND GRAVEL

Material	Percent By Weight	Percent By Volume
Gravel Material		
Quartz and Quartzite - dense, hard, tough, crystalline, particles consisting entirely of SiO_2 but with some slight iron staining.	56%	
Sandstone - hard, tough, high-silica particles but containing abundant iron as a heavy stain deposit and/or a cementing agent.	24%	
Sandstone - hard, tough, high-silica particles containing a minor amount of iron as a stain.	3%	
Chert - hard, tough particles consisting of microcrystalline quartz and chalcedony. The chalcedony is about 90 to 99% SiO_2 and minor to moderate amounts of iron and aluminum compounds.	13%	
Igneous and Metamorphic Rocks - dense, hard, tough, crystalline particles which consist of major to moderate amounts of SiO_2 and minor to moderate amounts of ferro-magnesium and alumina compounds.	3%	
Weathered Particles - soft, crumbly, iron-rich particles which may contain moderate amounts of silica.	1%	
Sand Material		
Quartz - hard, tough, crystalline grains of SiO_2.		95.1%
Sandstone and Siltstone - hard, tough particles consisting of well-cemented quartz grains.		4.4%
Weathered Sandstone - friable, easily-broken particles consisting of poorly-cemented quartz grains.		0.5%

Refuse was unloaded on one of the graded ramps, spread in .6 m lifts and compacted with a crawler tractor weighing approximately 17,200 kg. A total volume of 665 cubic meters of refuse was placed in the test cell. The wet weight of the refuse was 395 metric tons. The mean wet refuse density was 592 kg/cubic meter and the mean dry density 429 kg/cubic meter. The approximate height of the lifts as they existed in the center of the cell after construction are shown in Figure 3.

Probes were placed as the test cell was constructed. Figure 4 depicts a plan view of the test cell and the vertical point locations at which probes were installed. Table 3 presents the number and type of probes installed at the various levels (Figure 3) in the cell.

Both thermistors and thermocouples were installed in the cell to determine temperature. Settlement plates and monuments were placed at various depths and locations within the cell. The type of plate used is shown in Figure 5. Riser pipes extended vertically upward in sections so that readings could be taken on the internal settlement. Twenty-five gas probes were installed at various depths and locations within the refuse and in the adjacent undisturbed soil. Gas and temperature probe design is depicted in Figure 6. Twenty-five Soiltest Model MC-310A moisture cells were also placed at various locations within the refuse, the soil cover, and the soil liner at the base of the test cell.

Approximately .6 m of soil was placed over the refuse and compacted to a wet density of 1877 kg/cubic meter at a moisture content of 18.7 percent (dry weight basis). The permeability, as determined by a constant head permeability test, was 3.15×10^{-5} cm/sec at a dry density of 1597 kg/cubic meter and a total head of .10 kg/cm^2. Soil classification is shown in Table 1.

A small weather station was constructed at the test site with instrumentation for measuring relative humidity, minimum-maximum temperatures, continuous temperatures, and amounts and rates of precipitation. Five shallow well sets were installed around the perimeter of the test cell. Each set of wells consisted of three separate pipes extending approximately 3, 1.5, and .9 meters below the ground surface. Two deep wells, 30 m and 38 m deep, were installed on the extreme southern and northern ends of the field site.

Test Cell #1 Refuse Composition

Residential solid waste generated in the northern Kentucky vicinity was placed in the test cell. Two sets of samples were drawn from the refuse for analysis. One set consisted of a statistically determined number of samples withdrawn as the trucks unloaded that was bagged and taken to the laboratory for moisture and chemical analysis. For composition determination, a second set, 3 percent by wet weight of each truckload, was deposited sequentially in a windrow. Based on its length and width, the required number of 136 kg samples was determined statistically and extracted at random locations, bagged, and shipped for manual sorting and chemical analysis. Because the samples were extracted from particular positions from within the windrow, the composition of the refuse at particular levels within the test cell could be determined. These samples were sorted into eleven categories. The results

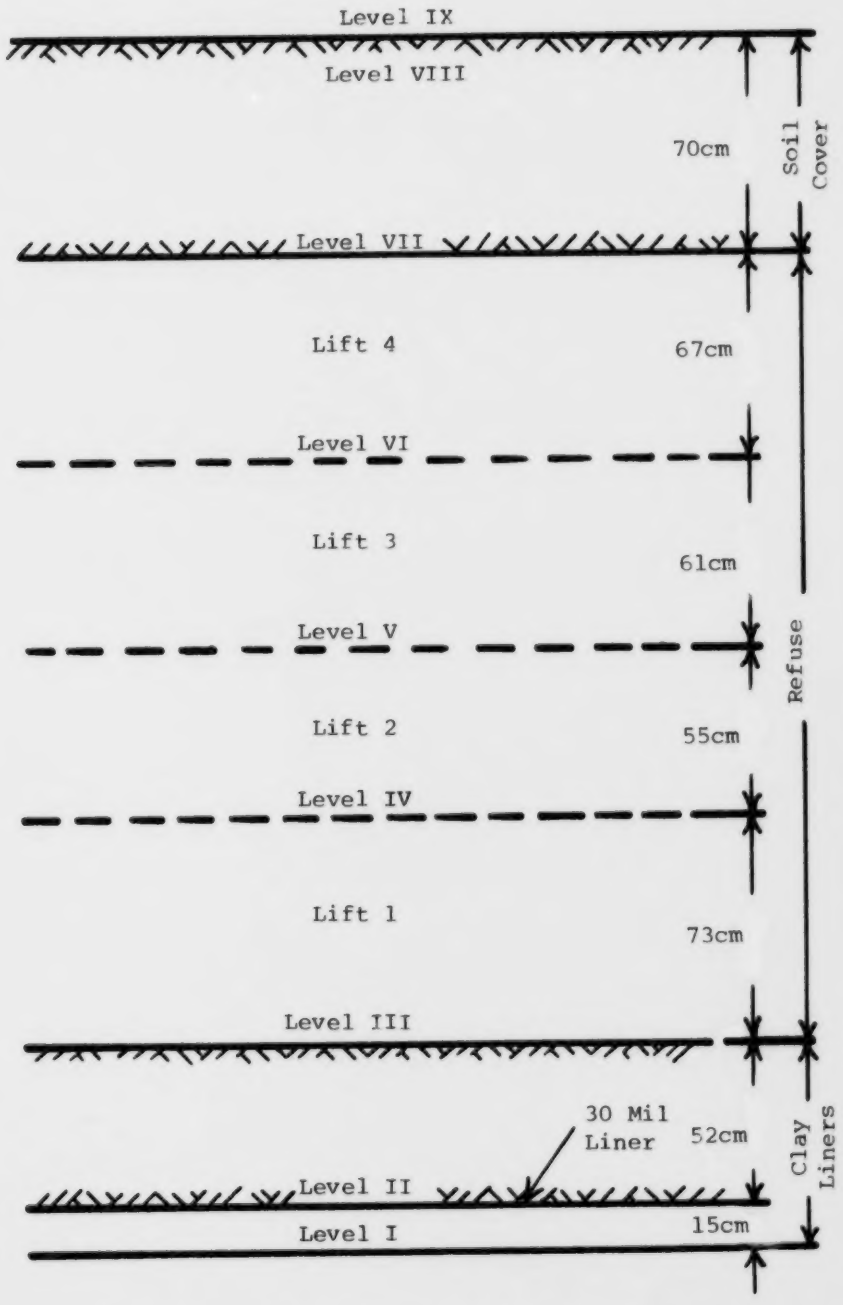
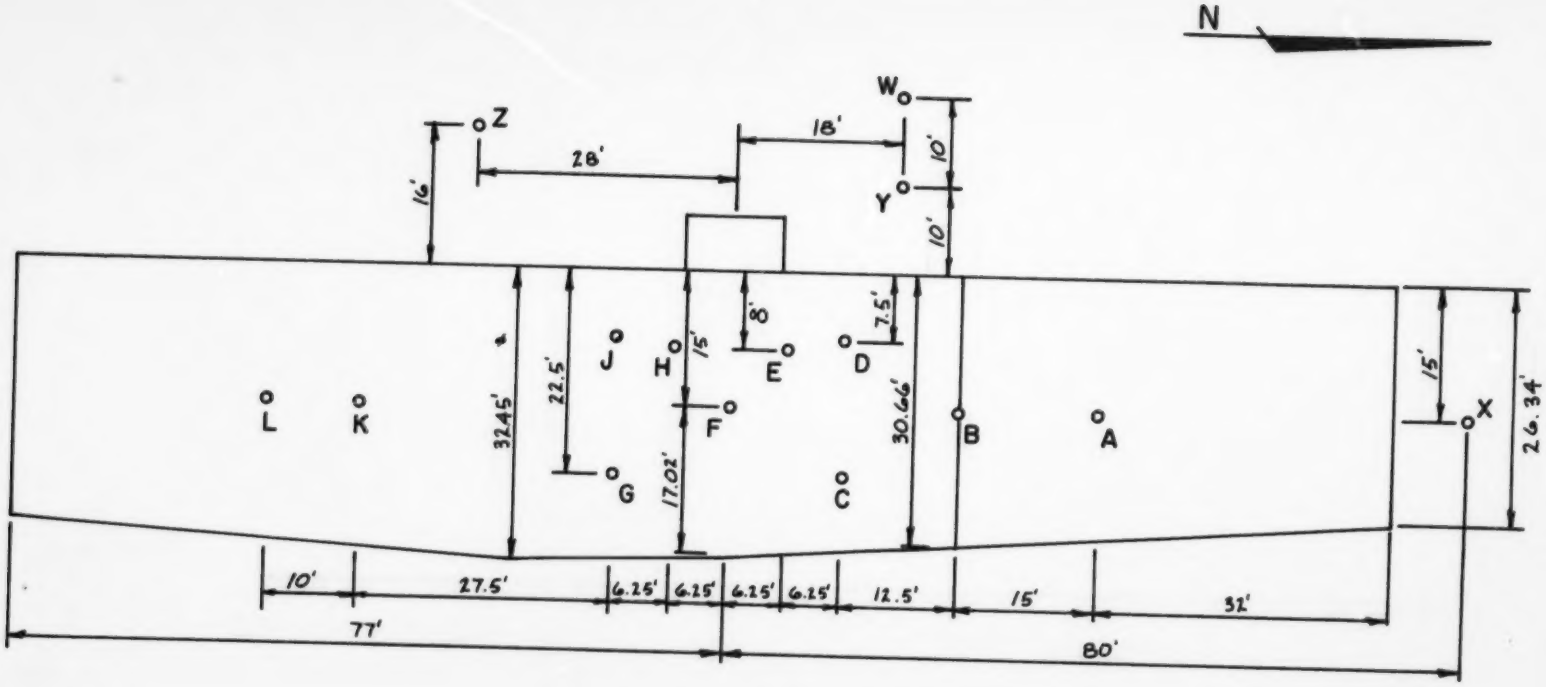


Figure 3. Refuse lifts and levels - Cell #1



SCALE: 1" = 20'

FIGURE 4. PLAN VIEW OF TEST CELL 1

TABLE 3. PROBE COUNTS AND LOCATIONS - T.C. #1

LEVEL	PROBE COUNT						PROBE LOCATION					
	MO	ST	GS	TM	TC	V	MO	ST	GS	TM	TC	V
I	4	--	2	--	2	--	C,G D,J	--	F,B	--	F,B	
II	4	--	2	--	2	--	C,G, D,J	--	F,B	--	F,B	
III	4	1	2	2	2	--	C,G, D,J	G	F,B	F,B	F,B	
IV	3	--	4	4	4	12	E	--	B,F E,H	B,F E,H	B,F E,H	E,H
V	3	5	4	4	5	12	E	C,D,G, J,K	B,F, E,H	B,F, E,H	A,B,F, E,H	E,H
VI	3	4	4	4	5	12	E	C,D, G,J	B,F E,H	B,F, E,H	A,B,F, E,H	E,H
VII	2	6	2	--	3	--	B,F	C,G,D, J,K,L	B,F	--	A,B,F	--
VIII	2	--	2	--	3	--	B,F	--	B,F	--	A,B,F	--
IX	--	6	1	1	1	--	--	C,G,D, J,K,L	F	F	F	--
TOTAL	25	22	23	15	27	36						

Code: MO - Moisture
ST - Settlement
GS - Gas
TM - Termistor
TC - Thermocouple
V - Virus

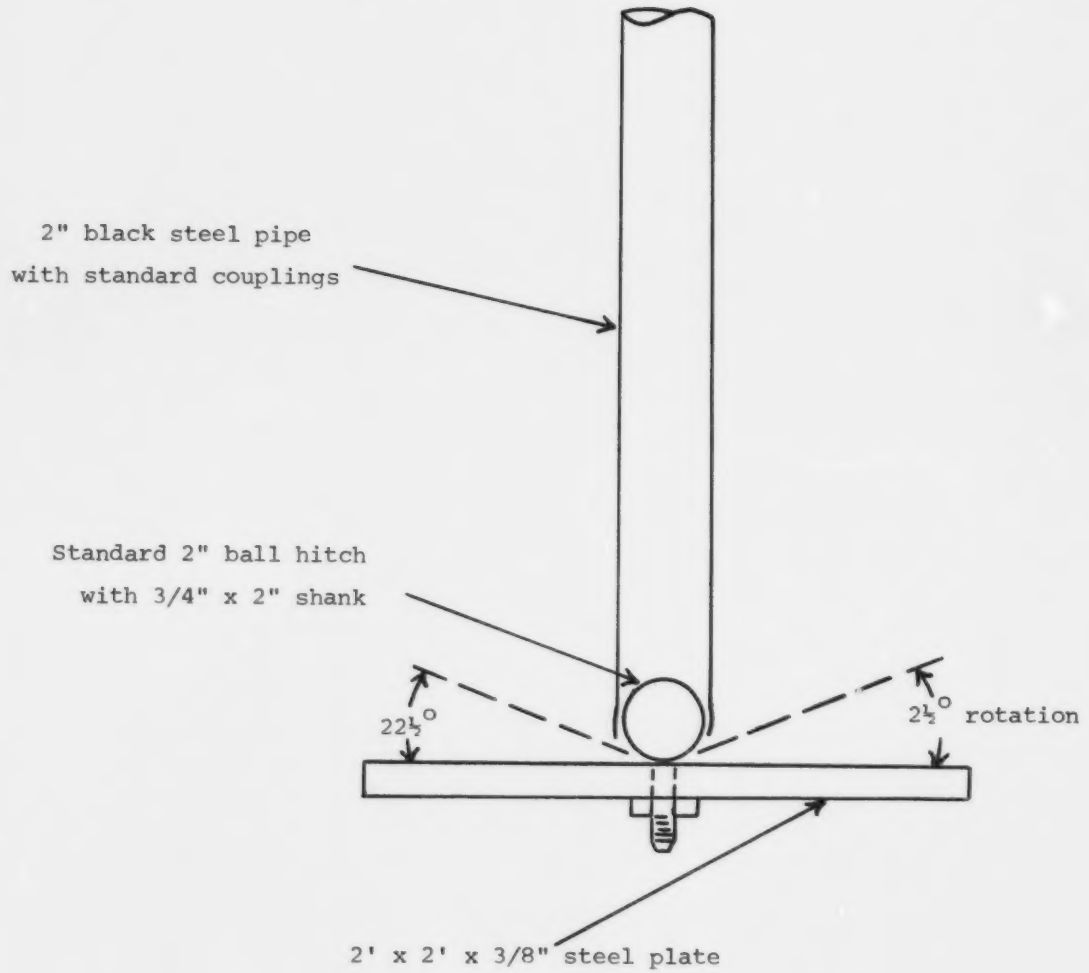


Figure 5. Settlement Plate - Cell 1

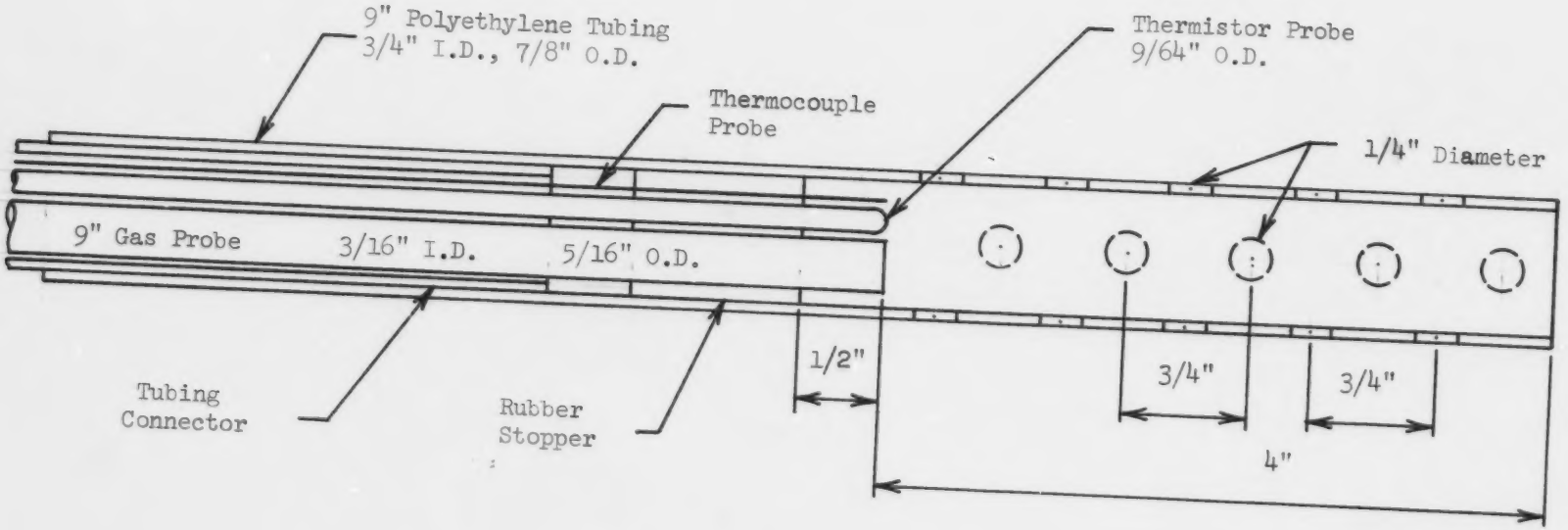


FIGURE 6. GAS AND TEMPERATURE PROBE

of the windrow sampling are presented in Table 4, along with refuse composition as averaged from other cities.

The forty samples obtained for moisture and chemical analysis, varying in weight from 4.5 to 9.5 kg, were dryed in a large industrial oven at 103°-105 C.° The mean moisture content of these samples was 42.7 percent on a dry weight basis and 29.9 percent on a wet weight basis. Fourteen of these samples were ground to a 2 mm particle size after as much of the glass and metal components as practical were removed and discarded.

Fifty gram portions were removed from each final sample, mixed with 750 ml of distilled water and allowed to stand for 16-20 hours with occasional stirring during the first few hours. Each mixture was then filtered with suction through a #3 Whatman filter paper. The residue on the paper was washed with successive 250 ml portions of distilled water and the filtrate and washings were diluted to a final volume of two liters. A total of 14 parameters were determined on each extract and where possible on the corresponding unextracted refuse. The resulting data is shown in Table 5.

The pH values for the solid samples were obtained by suspending one gram in 50 ml of water and also by mixing one gram with the minimum amount of water which would give a slurry in which the electrode could be immersed. The cations were determined by atomic absorption. The COD values were obtained per the method proposed by Lossin[3].

Test Cells 2A, 2B, 2C

Four additional test cells containing municipal solid waste were constructed at the Boone County Field Site during August 1972.[4] Three of the cells, 2A, 2B, 2C, were enclosed in identical cylindrical steel pipes, 1.83 m in diameter and 3.66 m long. The fourth test cell, 2D, was an 8.53 m square field cell constructed similarly to a normal sanitary landfill cell. These units were constructed to compare the performance of small-scale systems with a field-scale landfill cell and to evaluate the variations within the three small cells as measured by leachate quantity and characteristics, gas composition and temperature.

The steel pipes containing cells 2A, 2B and 2C were constructed of 4.8 mm hot-rolled steel plate coated on both sides with cold tar epoxy 1.5-2.0 mm thick. The pipes were placed vertically in an excavation on 150 mm thick reinforced concrete pads. Each pad contained a trough system with a 51 mm diameter slotted PVC pipe for leachate collection and flow to a central collection well, as shown in Figure 7. After installation of the pipes a 7.6 mm thick concrete overlay was placed around the pipes to prevent lateral movement. A fiberglass coating was applied to the concrete pad inside the pipe and .3 m up the interior walls of the pipe as protection against contact with leachate. The interior of the collection trough was backfilled with silica gravel and then .3 m of silica sand was placed at the bottom of each pipe. Earth backfill was placed around the exterior of the pipes to within 150 mm of the tops of the pipes.

TABLE 4. REFUSE COMPOSITION - T.C. #1

Waste Constituent	Mean Percent Total Sample By Wet Weight		
	Truck Sample	Windrow Sample	Average Composition of Residential Solid Waste in 21 U.S. Cities[a]
Food	4.1	4.4	18.2
Garden	9.9	9.5	7.9
Paper	54.7	51.7	43.8
Plastics, Rubber, Leather	4.3	8.0	3.0
Textiles	3.9	4.7	2.0
Wood	2.0	1.9	2.5
Metals	7.8	8.1	9.1
Glass, Ceramics	6.0	6.5	9.0
Rock, Dirt, Ash	2.0	1.6	3.7
Fines	4.6	2.9	--
Diapers	0.6	0.8	--

a. See Reference 2

TABLE 5. CHEMICAL ANALYSIS OF SOLID WASTE AND EXTRACTS - T.C. #1

Cell Lift Number	Percent Discard	pH			Conductivity[d]	Kjeldahl Nitrogen		
		Slurry[a]	Standard[b]	Extract[c]	Extract[c]	Solid[f]	Extract[c,e]	
1	20.9	6.0	6.5	6.4	443	6.6	1.2	30.0
1	29.7	5.8	6.3	5.7	398	3.8	0.4	10.0
2	13.2	5.9	6.3	6.1	370	3.4	1.4	35.0
2	33.8	5.5	5.8	6.3	163	2.8	0.7	17.5
2	14.7	5.9	6.3	4.6	563	5.7	1.0	25.0
3	30.9	5.7	6.2	4.6	1158	13.8	2.0	50.0
3	3.4	5.8	6.1	5.3	568	5.0	1.4	35.0
3	6.1	5.8	6.3	5.9	448	4.4	0.6	15.0
3	7.0	5.8	6.2	5.0	508	6.4	1.8	45.0
4	7.1	5.0	5.5	5.4	418	5.8	0.4	10.0
4	7.8	5.5	5.9	5.3	248	3.1	0.3	7.5
4	10.9	6.0	6.5	6.3	848	12.4	1.5	37.5
4	5.8	5.3	5.6	6.1	713	8.2	2.0	50.0
4	13.8	6.6	7.3	6.6	408	4.0	2.1	52.5

a. 1 gram sample with minimum water added
b. 1 gram sample plus 50 ml distilled water
c. Filtered (Whatman #3) extract of 50 g solid waste mixed occasionally with 750 ml distilled water for 16-20 hrs.
d. micromhos/cm
e. Extract of solid waste expressed as mg/l in first column and as mg of parameter per gram of extracted solid waste in second column.
f. mg/g

TABLE 5. CHEMICAL ANALYSIS OF SOLID WASTE AND EXTRACTS - T.C. #1 (continued)

EDTA Hardness[g]			COD			Iron			Calcium		
Solid[f]	Extract[c,e]		Solid[f]	Extract[c,e]		Solid[f]	Extract[c,h]		Solid[f]	Extract[c,e]	
25.1	2.45	61.3	904	2.12	53.0	1.31	<1	<25	9.40	0.59	14.7
21.5	3.10	77.5	906	2.64	66.0	0.85	N.D.		4.89	0.84	21.0
16.1	5.75	143.8	1053	2.12	53.0	0.45	N.D.		3.87	1.00	25.1
37.8	3.51	87.8	890	2.36	59.0	3.02	<1	<25	8.68	0.60	15.0
16.1	10.90	272.5	918	3.16	79.0	0.58	N.D.		4.35	1.58	39.4
36.6	9.20	230.0	832	2.40	60.0	2.02	1.3	29.4	10.70	1.24	31.0
15.3	5.49	137.3	1110	4.50	113.0	0.53	<1	<25	2.55	0.68	17.0
29.0	10.90	271.5	1021	3.44	86.0	0.83	N.D.		7.56	0.93	23.2
21.0	9.06	226.5	959	3.72	93.0	1.05	<1	<25	8.07	1.04	26.0
12.5	4.20	105.0	955	2.64	66.0	0.36	<1	<25	2.23	0.69	17.3
12.2	4.31	107.8	1087	0.80	20.0	0.99	<1	<25	25.83	0.60	14.9
149.5	15.80	395.3	463	1.32	33.0	6.05	<1	25	2.55	1.70	42.4
42.9	9.42	235.5	792	3.44	86.0	1.17	1	<25	11.18	1.46	36.6
34.1	3.40	85.0	849	0.80	20.0	2.72	N.D.		10.79	0.63	15.7

c. Filtered (Whatman #3) extract of 50 g solid waste mixed occasionally with 750 ml distilled water for 16-20 hrs.

e. Extract of solid waste expressed as mg/l in first column and as mg of parameter per gram of extracted solid waste in second column.

f. mg/g

g. as $CaCO_3$

h. In micrograms/g or micrograms/l

j. N.D. - not detected by atomic absorption

TABLE 5. CHEMICAL ANALYSIS OF SOLID WASTE AND EXTRACTS - T.C. #1 (continued)

Magnesium			Potassium			Sodium			Sulfate		
Solid[f]	Extract[c,e]		Solid[f]	Extract[c,e]		Solid[f]	Extract[c,e]		Solid[f,k]	Extract[c,e]	
0.81	0.18	4.5	1.97	2.10	52.5	1.66	1.50	37.4	6.60	1.57	39.3
0.54	0.20	5.1	1.80	1.94	48.5	1.31	1.23	30.7	5.20	1.04	26.0
0.50	0.20	4.9	0.97	1.16	29.0	1.03	0.98	24.5	3.80	1.79	44.8
4.30	0.12	2.9	0.44	0.35	8.7	0.53	0.50	12.4	5.32	0.80	20.0
0.76	0.31	7.8	2.63	2.54	63.4	1.38	1.32	12.4	2.56	1.40	35.0
0.90	0.38	9.6	4.12	3.91	97.8	6.49	5.55	138.8	4.68	1.38	34.5
0.66	0.23	5.7	4.24	4.20	105.1	1.03	1.07	26.8	3.07	1.50	37.5
1.92	0.14	3.5	0.75	0.86	212.6	4.32	2.21	55.3	5.52	1.03	25.8
0.59	0.21	5.3	1.50	1.46	36.6	1.90	2.00	50.1	5.18	1.52	38.0
0.25	0.13	3.3	1.42	1.74	43.5	2.90	1.82	45.6	2.36	1.63	40.8
0.41	0.09	2.3	0.71	0.82	20.6	0.84	0.88	22.1	3.01	1.52	38.0
9.97	0.56	13.9	3.01	3.18	79.6	3.44	2.68	66.9	6.83	3.46	86.5
0.67	0.28	6.9	2.91	2.27	56.7	3.60	3.12	78.0	3.19	1.18	29.5
1.01	0.07	1.7	3.31	1.08	27.1	1.64	0.59	14.7	5.11	2.07	51.8

c. Filtered (Whatman #3) extract of 50 g solid waste mixed occasionally with 750 ml distilled water for 16-20 hrs.

e. Extract of solid waste expressed as mg/l in first column and as mg of parameter per gram of extracted solid waste in second column.

f. mg/g

k. Total sulfur determined and calculated as sulfate.

TABLE 5. CHEMICAL ANALYSIS OF SOLID WASTE AND EXTRACTS - T.C. #1 (continued)

Total Phosphate	Chloride		
Solid[f]	Solid[f]	Extract[c,e]	
22.4	4.3	1.53	38.2
5.0	44.8	1.88	47.0
4.4	2.8	1.08	27.1
3.4	1.2	0.24	5.9
4.9	2.9	2.01	50.2
10.2	11.6	8.56	213.9
2.4	2.5	2.22	55.5
2.6	3.6	3.04	76.1
1.8	3.0	2.51	62.8
2.0	2.0	2.26	56.6
4.4	6.2	0.95	23.8
4.4	9.2	3.56	89.0
5.8	7.6	4.31	107.7
2.0	4.6	2.13	53.2

c. Filtered (Whatman #3) extract of 50 g solid waste mixed occasionally with 750 ml distilled water for 16-20 hrs.

e. Extract of solid waste expressed as mg/l in first column and as mg of parameter per gram of solid waste in second column.

f. mg/g

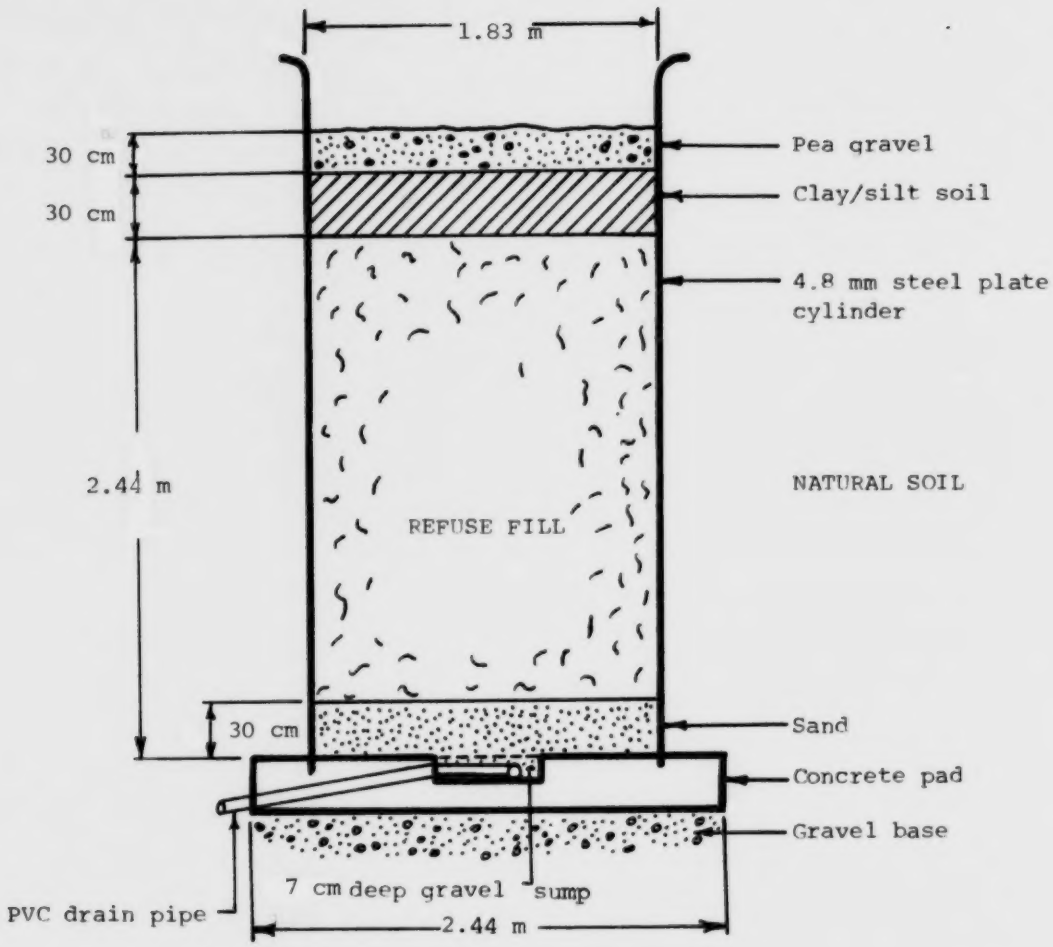


Figure 7. Cell Construction Details - Cells 2A,B,C

Refuse was then placed in the pipes in 90-135 kg increments to a total depth of 2.56 m. Each increment was compacted by dropping a 135 kg weight from approximately 1.2 m above the refuse until no further compaction was apparent. Temperature and gas probes were placed within the cell during placement of the refuse as shown in Figures 8 and 9. After refuse placement a 300 mm compacted soil cover from the site was applied. This soil was then covered by 300 mm of pea gravel to allow rapid percolation of rainfall and to minimize evaporation.

Construction of Cell 2D

Cell 2D was constructed in an excavation 8.53 m square and 3.20 m deep. The base of the cell was shaped with sand for drainage and a 7.6 mm thick low density polyethylene liner (Staff Industries, Inc.) was placed along the cell side walls and base. A slotted PVC pipe was placed along the center line of the base of the cell for leachate collection and gravity drainage to the collection well. Silica gravel was then placed on the top and sides of the collection pipe. The entire base of the cell and liner was then covered with 300 mm of silica sand. Plywood sheets were placed against the synthetic liner on the sidewalls for protection from puncture and tearing during cell filling. The construction details are shown in Figure 10.

A case 450 (7t) bulldozer was lowered into the cell by a crane. Refuse was added by the crane from a stockpile and compacted by the bulldozer. Temperature and gas probes were placed during the filling at locations shown in Figure 10. A 300 mm layer of compacted soil cover was placed over the 2.44 m of refuse. To promote uniform percolation of rainfall into the refuse cell, a berm system, as shown in Figure 11, consisting of 150 mm high triangular-shaped clay berms, was hand constructed on top of the soil cover. A 300 mm layer of pea gravel was placed over the entire soil cover. Excess liner material was folded over the top of the plywood sheeting and covered with earth on the outside of the plywood walls.

Refuse Composition, Cells 2A-2D

Residential solid waste from municipal and private collection routes was obtained for the test cell.[4] 149.9 metric tons of refuse from 23 truckloads was placed in a stockpile. Approximately 10% of the refuse in each truck was removed from the ordered stockpile and deposited at a position in a windrow in accordance with the arrival time of the refuse.

This windrow was divided into quarters on a weight basis as shown in Figure 12. Random assignments of sample locations within each quarter were made and twelve 136 kg samples were removed at that location for compositional analysis. Then approximately 725 kg of refuse was removed from each of the quadrants at the locations designated in Figure 12 for use in the cells. The pipes were filled sequentially and the refuse was always in the order quadrant 1, 2, 3, 4. Refuse was removed by hand, weighed, and placed in the pipes. Several samples were taken during filling for subsequent moisture analysis.

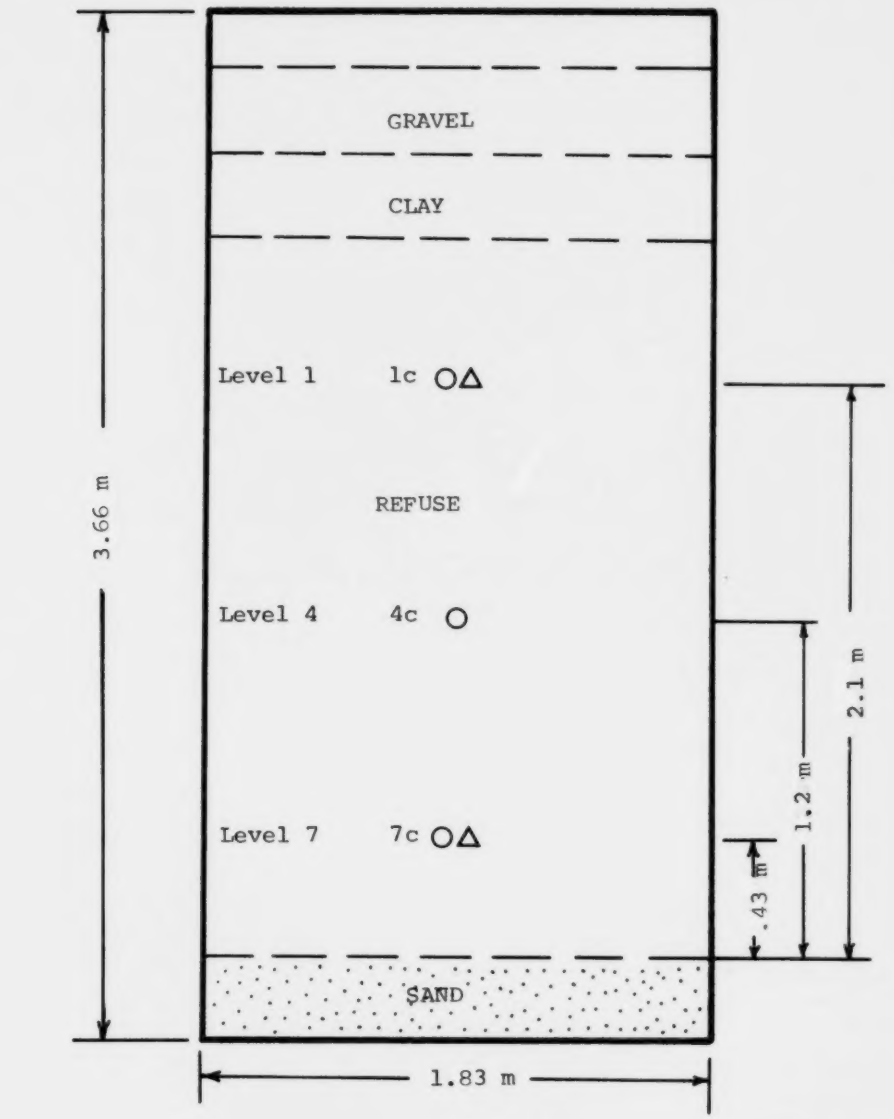


Figure 8. Construction details for cells 2A and 2C.

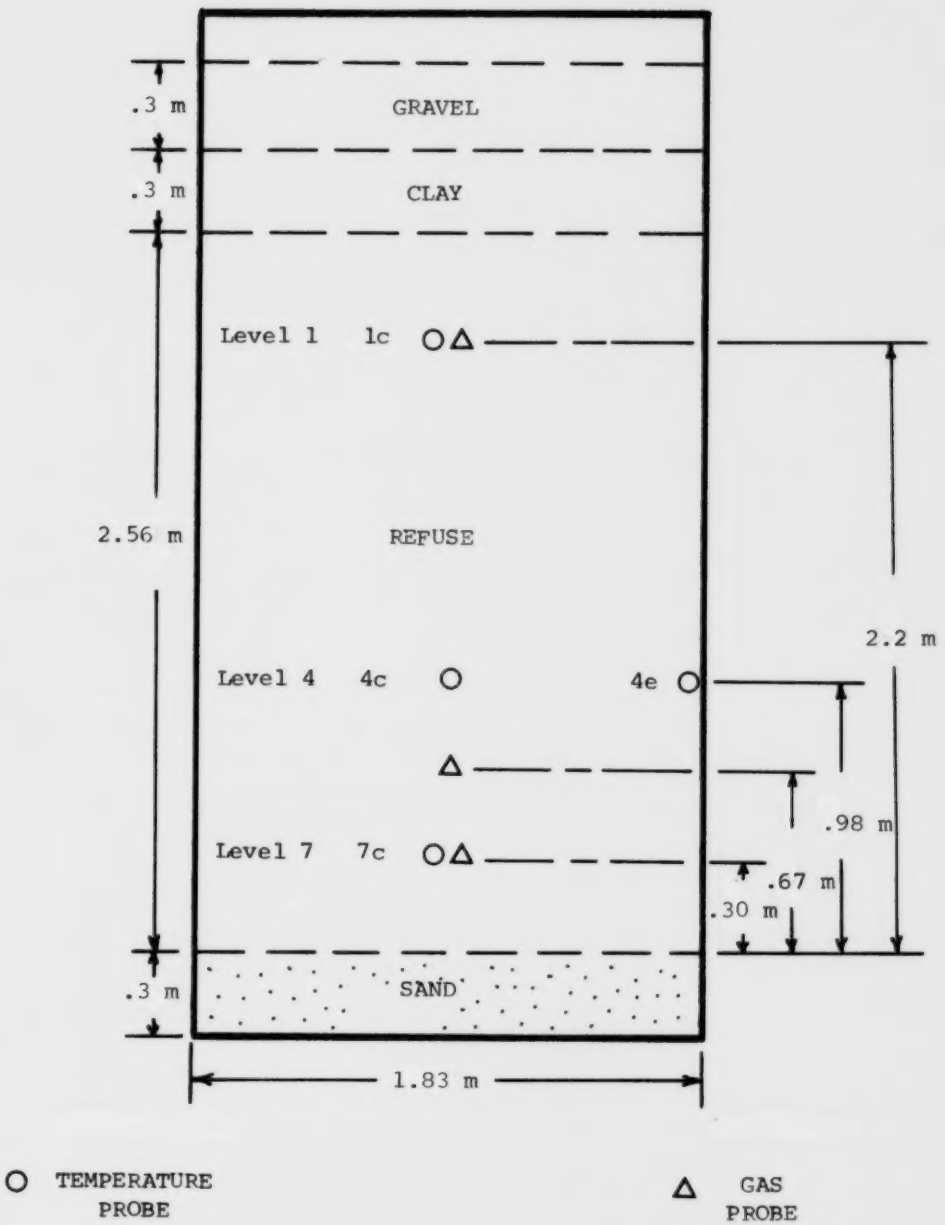
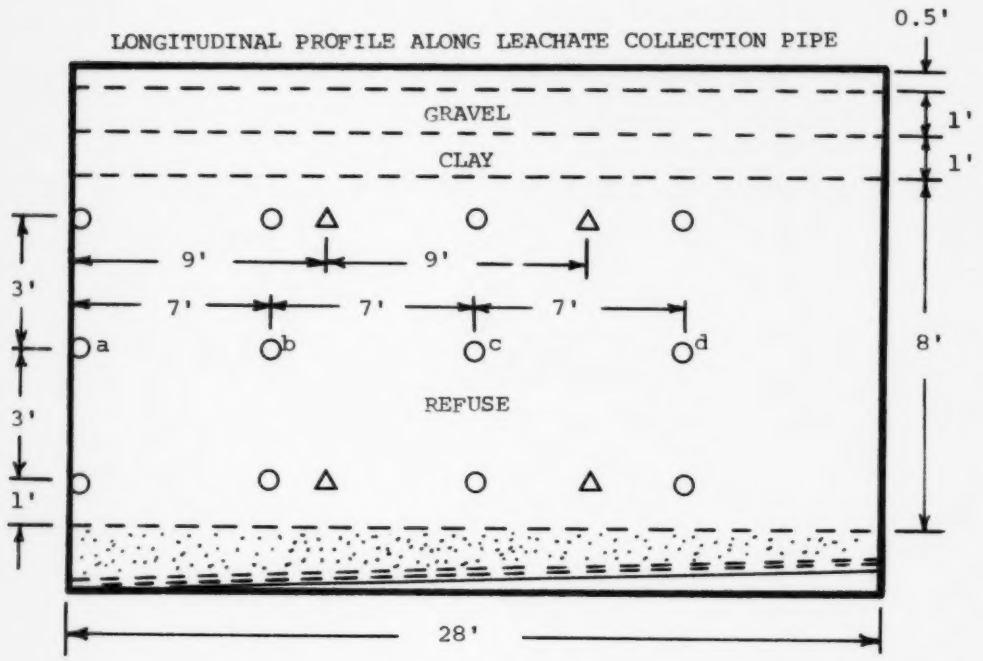


Figure 9. Construction details for cell 2B.



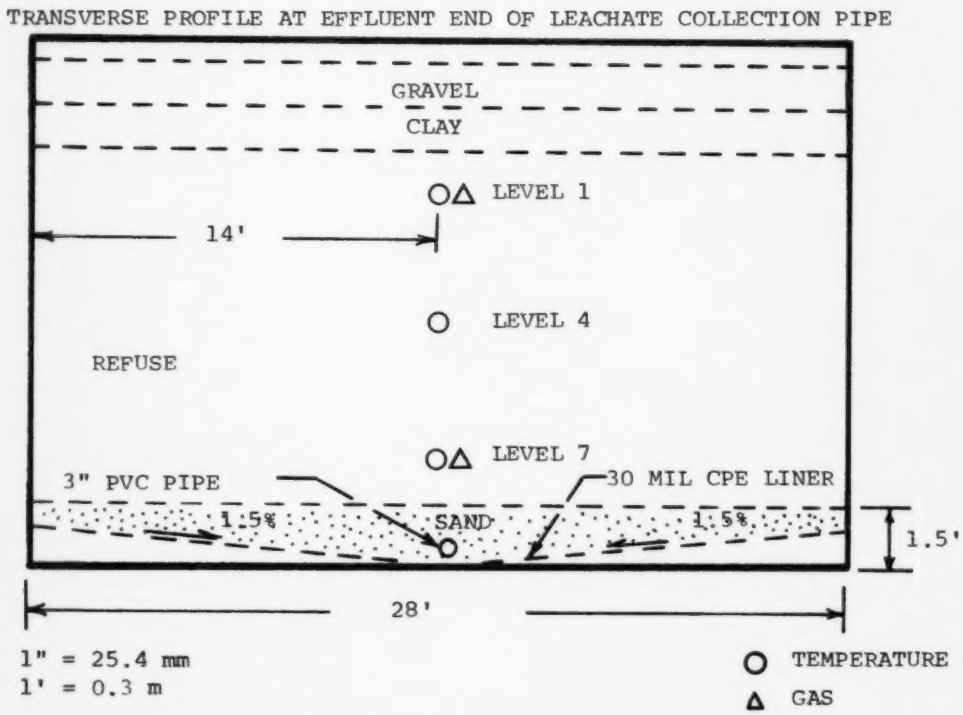


Figure 10. Construction details for cell 2D.

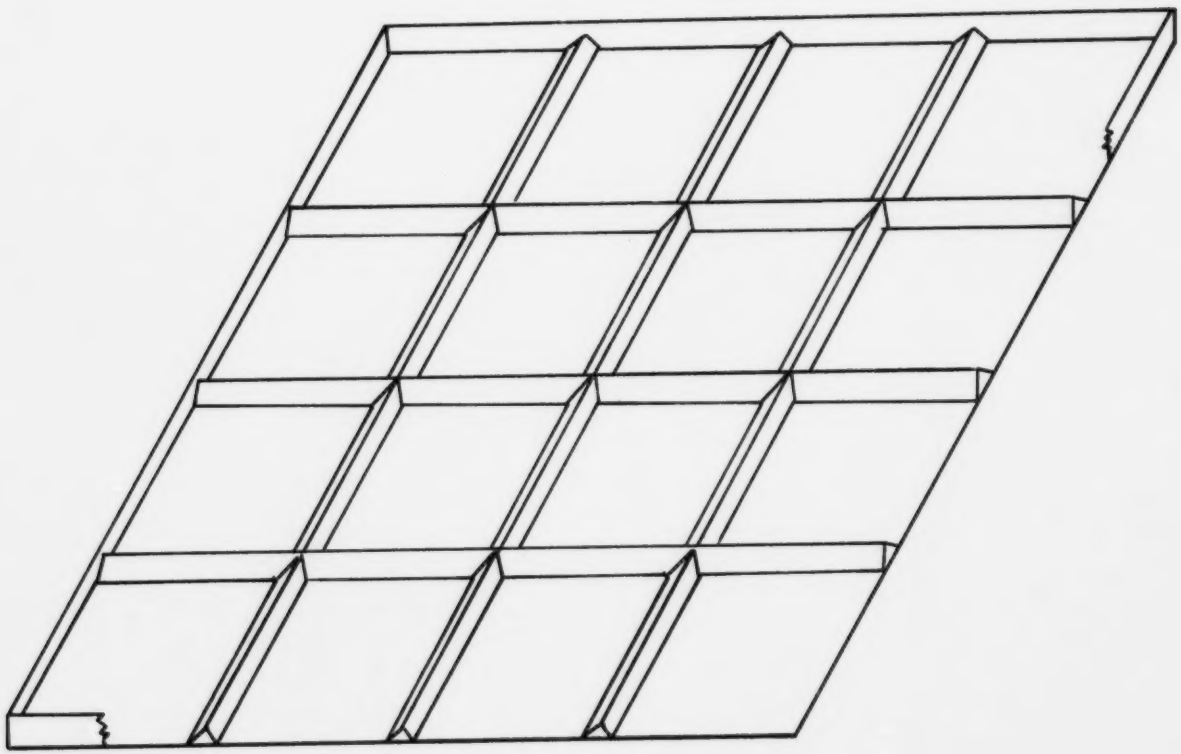


Figure 11. Construction of clay cover for cell 2D

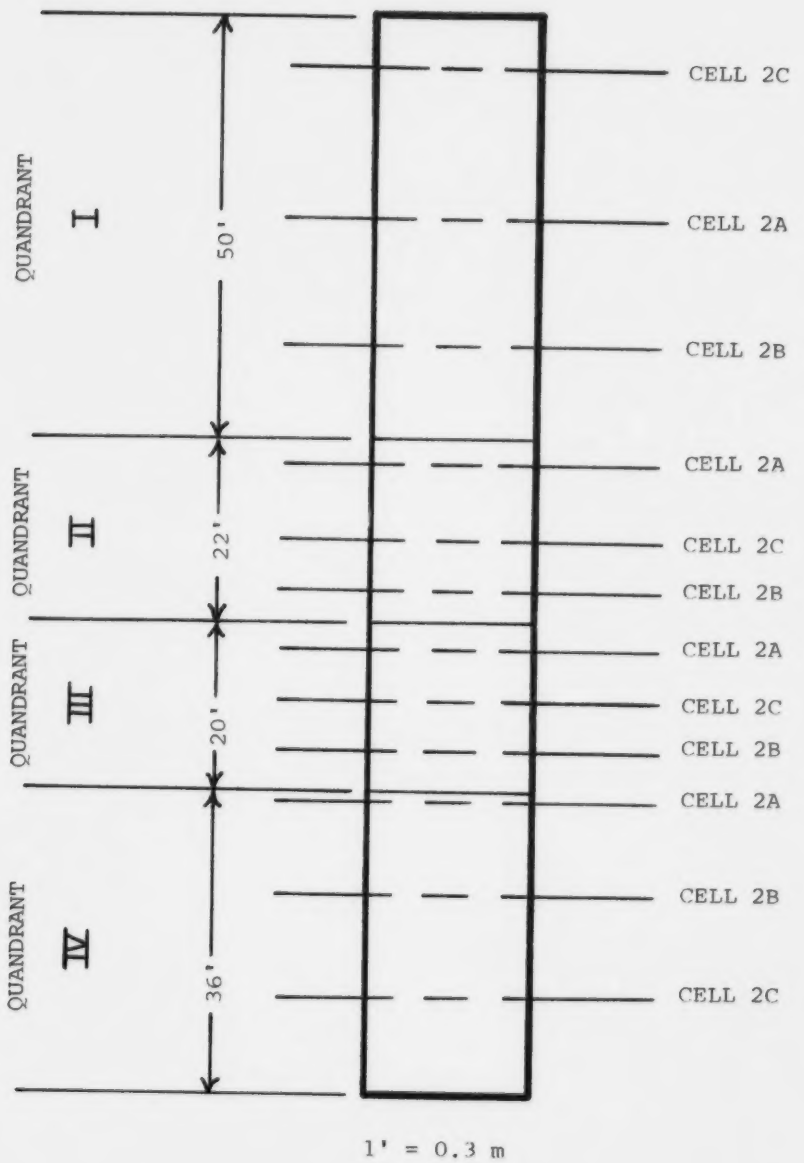


Figure 12. Locations in windrow where refuse was obtained for cells 2A, 2B, and 2C.

Refuse from the main stockpile was added to cell 2D by means of a clamshell. The refuse was placed so that each of the four lifts in the cell came from the quadrant in the stockpile corresponding to the same windrow location. Estimates of refuse density were made while filling in an effort to achieve a similar refuse density to that obtained in the smaller cells. However, additional compaction of the lower lifts of refuse occurred as upper layers were being compacted and the final density was in excess of that desired.

Composition analysis was performed by hand sorting the twelve original samples. The results are presented in Tables 6 and 7. That fraction showing as fines represents the material passing through a 25.4 mm square mesh sieve not readily separated into any of the other categories. Using the method of Stell and Torrie[5] for unpaired observations and unequal variances the significance of the variations in refuse component means for cells 2A, 2B and 2C was determined. Results are presented in Table 8. None of the variations were significant at the 10% level. Therefore, any variations in the performance of cells 2A, 2B and 2C cannot readily be attributed to difference in the quantities of refuse within each category. The possibility of performance differences due to variations between the actual composition within each category was not examined.

Twenty samples of approximately 4.5 kg of the separated components were taken for moisture analysis. Samples were dried to a constant weight at 100-105°C for 24 hours. The samples had been stored for approximately 3 weeks in sealed plastic bags to prevent moisture changes, therefore transfer of moisture from one category to another was not prevented. The results are presented in Table 9.

A number of grab samples were also obtained during refuse placement for moisture determination. The results are presented in Table 10. The mean moisture content of the windrow samples was 24.1% with a standard deviation of 8.7%. The mean moisture content of the stockpiled samples was 31.9% with a standard deviation of 12.9%. A statistical comparison of sample means[5] revealed no significant differences in moisture at the 5% level. Therefore, any variations in the performance of cell 2D as compared to 2A, 2B and 2C cannot readily be attributed to differences in initial moisture content.

The amount of refuse, wet weight, placed in cells 2A, 2B and 2C was 2,639 kg, 2,898 kg, and 2,813 kg, respectively. The wet densities were 392, 431, and 418 kg/m^3. Refuse placed in cell 2D was calculated to be 106.2 t at an in-place wet density of 598 kg/m^3. Initial refuse moisture content, by wet weight, was 22.5% for 2A, 27.1% for 2B, 24.1% for 2C and 31.8% for 2D. A summary of cell data is contained in Table 11.

Samples obtained for chemical analysis of the refuse were frozen for future analysis. These samples were inadvertently destroyed during transfer of the EPA Office of Solid Waste from Cincinnati to Washington, D.C. in 1973.

TABLE 6. COMPOSITION OF RANDOM REFUSE SAMPLES

Windrow Sample Location Quad.,	Cell	Total Weight Separated[a]	Component-Percent by Wet Weight									
			Food Waste	Garden Waste	Paper	Plastics, Rubber, Leather and Textiles	Wood	Metals	Glass	Ash, Rocks and Dirt	Diapers	Fines
I	2A	131	4.48	8.21	52.7	7.62	0.45	7.13	6.23	1.36	0.66	11.17
I	2B	128	4.26	10.05	39.0	13.6	2.38	15.62	8.81	3.41	0.53	2.34
I	2C	118	4.96	7.42	46.8	5.08	11.58	9.54	6.00	0	0.038	8.58
II	2A	128	3.43	1.20	38.75	11.78	20.9	13.6	6.51	0.78	0.39	2.62
II	2B	134	2.19	28.6	44.7	6.75	0.47	7.79	7.89	0	0.067	1.55
II	2C	129	1.83	1.62	53.4	11.15	1.58	10.34	11.53	3.41	0.457	4.65
III	2A	131	1.52	9.34	58.6	13.3	0.415	4.92	6.16	0	1.87	3.81
III	2B	130	3.49	12.55	49.2	11.81	0.94	8.28	6.54	0	0.07	7.06
III	2C	128	3.68	21.65	40.8	14.0	7.25	7.01	2.44	0	0.46	2.62
IV	2A	131	2.33	2.05	65.8	9.96	1.63	6.74	5.10	0	0.90	5.52
IV	2B	130	10.18	4.47	46.9	7.77	0.42	10.50	11.89	0.63	5.55	1.71
IV	2C	136	12.11	2.74	53.8	11.10	1.20	9.07	6.26	0	0.234	3.42

a. kilograms

TABLE 7. REFUSE COMPOSITION FOR CELLS 2A, 2B, 2C and 2D

Cell	Statistic	Refuse Component - Percent by Wet Weight									
		Food Waste	Garden Waste	Paper	Plastics, Rubber, Leather and Textiles	Wood	Metal	Glass	Ash, Rocks and Dirt	Diapers	Fines
2A	Mean	2.94	5.20	53.96	10.66	5.85	8.10	6.00	0.535	0.955	5.78
	Stand. Dev.	1.29	4.17	11.5	2.45	10.0	3.79	0.62	0.66	0.64	3.79
2B	Mean	5.03	13.92	44.95	9.98	1.05	10.55	8.78	1.01	1.56	3.17
	Stand.Dev.	3.54	10.36	4.37	3.25	0.92	3.58	2.27	1.63	2.67	2.62
2C	Mean	5.65	8.36	48.7	10.33	5.40	8.99	6.56	0.85	0.30	4.82
	Stand.Dev.	4.50	9.21	6.17	3.75	4.96	1.42	3.75	1.71	0.20	2.64
2D*	Mean	4.54	9.16	49.20	10.33	4.10	9.21	7.11	0.799	0.936	4.59
	Stand.Dev.	3.29	8.44	8.16	2.91	6.29	3.01	2.63	1.29	1.54	2.99

*Determined from all observations for 2A, 2B, and 2C

TABLE 8. COMPARISON OF SAMPLE MEANS FOR CELLS 2A, 2B, and 2C

Refuse Component	Cell Comparison	t'[a]
Food Waste	2A-2B	1.110
	2A-2C	1.158
	2B-2C	0.217
Garden Waste	2A-2B	1.563
	2A-2C	0.625
	2B-2C	0.802
Paper	2A-2B	1.465
	2A-2C	0.806
	2B-2C	1.019
Plastics, Rubber, Leather and Textiles	2A-2B	0.334
	2A-2C	0.147
	2C-2B	0.141
Wood	2A-2B	0.951
	2A-2B	0.080
	2B-2C	1.724
Metals	2A-2B	0.941
	2A-2C	0.441
	2B-2C	0.810
Diapers	2A-2B	0.440
	2A-2C	1.941
	2B-2C	0.941
Fines	2A-2B	1.134
	2A-2C	0.416
	2B-2C	0.887

a. t statistic per reference 5. Means would be significantly different at the 10% level if $t' > 2.353$.

TABLE 9. MOISTURE CONTENT OF SEPARATED REFUSE COMPONENTS

Windrow Sample Location	Refuse Component	Percent Moisture	Percent by Weight of Component in Total Sample
Quad III Cell 2B	Fines	17.2	7.1
	Food	42.2	3.5
	Wood	15.4	0.9
	Garden	53.7	12.5
	Paper	25.4	49.2
	Plastics, Rubber, Leather & Textiles	15.5	11.8
	Metal	10.9	8.3
	Glass	0.44	6.5
			Σ = 99.8
Quad I Cell 2A	Fines	27.1	11.2
	Food	40.6	4.5
	Garden	54.3	8.2
	Paper	36.3	52.7
	Plastics, Rubber, Leather & Textiles	22.7	7.6
	Metal	7.8	7.1
	Glass	2.0	6.2
			Σ = 97.5
Quad III Cell 2C	Food	49.3	3.7
	Garden	44.1	21.7
	Paper	32.6	40.8
	Plastics, Rubber, Leather & Textiles	29.3	14.0
	Metal	4.6	7.0
			Σ = 87.2

TABLE 10. MOISTURE CONTENT OF REFUSE SAMPLES FOR CELLS 2A, 2B, 2C AND 2D

Sample Location			Wet	Percent Moisture by Wet Weight				
Windrow		Stockpile	Sample	Date Sample Obtained				
Quad	Cell	Quad	Weight[a]	8/14	8/15	8/16	8/17	8/18
I	2A		12.0	28.0				
I	2B		23.0	23.0				
I	2B		23.0	31.2				
I	2C		8.3	31.8				
I	2C		17.6		18.9			
III	2A		26.0	7.0				
III	2A		12.75	35.7				
III	2C		18.2		16.7			
IV	2A		18.0	19.4				
IV	2C		15.9		29.1			
		I	14.2			31.7		
		I	22.0		34.0			
		II	13.3			38.4		
		II	8.5			37.2		
		III	10.2				20.0	
		III	16.0				17.4	
		IV	21.0					56.3
		IV	11.0					20.0

a. kilograms

TABLE 11. SUMMARY OF CELL DATA

Item	Test Cell 1	2A	2B	2C	2D
Cover Soil Classification	CL	CL	CL	CL	CL
Depth of Soil Cover, m	.60	.30	.30	.30	.30
Surface Area of Refuse, m^2	432.3	2.627	2.627	2.627	72.83
Maximum Depth of Refuse, m	2.56	2.56	2.56	2.56	2.44
Mass of Refuse, kg (Dry)	286,000	2,046	2,113	2,135	72,450
Dry Density of Refuse, kg/m^3	429	304.3	314.1	317.6	407.7
Moisture Content of Refuse, % Wet Wt.	27.6	22.5	27.1	24.1	31.8

SECTION V

DATA COLLECTION AND ANALYSIS

LEACHATE QUANTITY

Test Cell #1

Leachate was initially collected from both the upper and lower pipes of Test Cell #1 approximately two months after cell construction. Cumulative leachate volume is shown in Figure 13. The observation unit adjacent to the cell in which leachate was collected collapsed in February 1979 and volume measurements after that time were not possible. At that time, 1.07 million liters of leachate had been collected, representing 27.5% of the precipitation recorded at the site.

The quantity of leachate from the lower pipe was equal to or greater than that volume from the upper pipe until January, 1972. This was caused by leaving the valve closed on the upper pipe except for weekly sampling, thereby inducing sufficient head to cause leakage into the lower pipe. After December 20, 1971 the upper pipe was allowed to drain freely through an S-trap into a sump in the observation unit, thereby greatly reducing the hydraulic head and consequently reducing the flow from the lower pipe.

The yearly quantities of leachate collected from both the upper and lower pipes and the percentage of the total from the lower are shown in Table 12. Flow quantity remained relatively constant after 1972 through a wide yearly variation in total leachate flow, indicating soil liner saturation and relatively constant head and soil permeability throughout the later years of cell life. Tests of the soil liner at closure[6] showed reductions in permeability of the soil of 2 to 3 orders of magnitude, from the original 2×10^{-5} to 4×10^{-7} to 2×10^{-8} cm/sec. Apparently this reduction must have occurred during the early part of the cell life (1971-72) in order for the flows to have remained so steady from 1973-1979.

One of the objectives of Test Cell #1 was to evaluate the effectiveness of the soil liner in containing leachate. While greater than 99% of the total leachate flow was collected from the upper pipe, soil liner drain efficiency estimating methods[7] predict as much as 90% of the flow should have passed through the soil liner at the as-built permeability. This indicates that the Hypalon® liner and the soil liner are functioning together and that the large percentage of the leachate collected in the upper pipe is not due to the soil alone. Apparently the Hypalon sheet blocks deep percolation, forcing flow along the refuse-soil interface, resulting in the high percentage of leachate

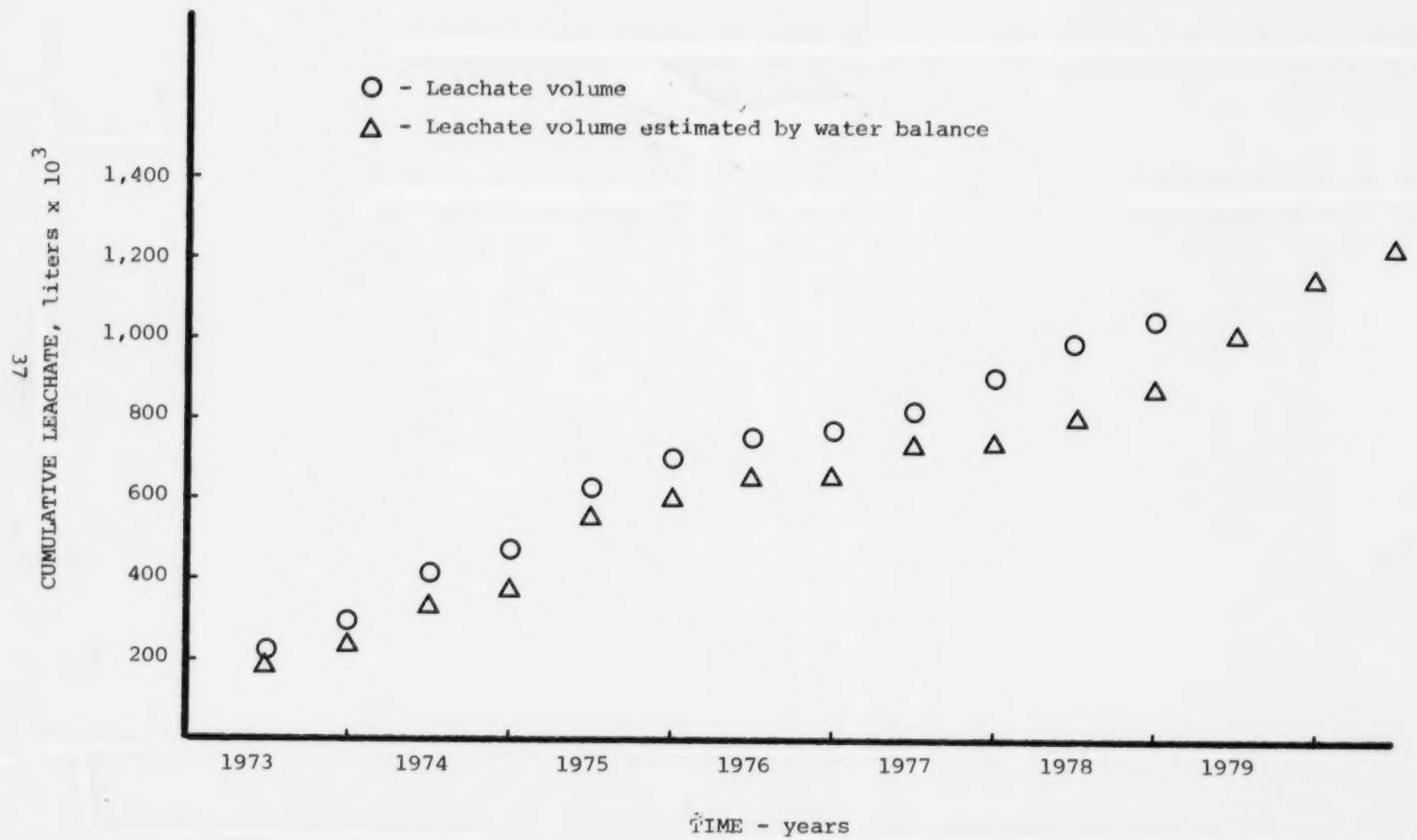


Figure 13. Cumulative leachate volume - Cell #1.

TABLE 12. YEARLY DISTRIBUTION OF LEACHATE - CELL #1

Year	Upper Pipe Volume[a]	Lower Pipe Volume[a]	% of Total From Lower Pipe
6/71-1/1/72	614	646	51.3
1972	50,500	1,104	2.1
1973	244,200	1,260	.51
1974	186,800	1,250	.66
1975	188,500	1,470	.77
1976	87,100	900	1.0
1977	115,900	1,140	.98
1/1/78-2/17/79	179,800	1,220	.67
Totals	1,053,414	8,990	.85

a. liters

collected in the upper pipe. If a free draining granular layer had been placed between the Hypalon® and the base of the soil liner a more difinitive evaluation of the soil liner effectiveness could have been made.

The leachate volume predicted using the water balance method[1] is shown with the cumulative leachate volume in Figure 13. In computing the water balance, mean monthly temperatures for Covington, Kentucky were used to compute the potential evapotranspiration[8]. The runoff coefficients for the wet and dry seasons were chosen as .17 and .13, as suggested for the type of soil and slope of the test cell[1]. The contributing surface of the cell was assumed to be 432.3 m^2, the surface area of the upper refuse lift. A soil moisture storage capacity of 125 mm for the .6 m depth of final cover was assumed. An additional 106,000 liters of water were assumed to be required to bring the entire cell and the soil liner to field capacity based on an estimated refuse field capacity of 330 mm/m of refuse[9]. Applying the water balance method with the above assumptions yielded the estimated percolation presented in Table 13 and Figure 13.

Through mid-February 1979 when volume measurements ceased, the water balance method predicted 991,600 l of leachate as compared to 1,060,000 l actually collected. This is remarkably accurate given the number of assumptions required, differing by only 6%. If yearly average evapotranspiration values had been used, rather than ones computed from the actual

TABLE 13. TEST CELL # 1 - ESTIMATED PERCOLATION

Month	Year - Percolation[a]									
	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Jan.		41	37	80	79	67	23	75	115	36
Feb.		37	32	32	105	62	18	5	90	32
Mar.		67	68	76	101	7	75	52	4	87
April		70	97	12	125	0	38	0	86	20
May		0	0	0	0	0	0	6	0	0
June	0	0	24	31	6	0	0	0	16	0
July	0	0	0	0	0	0	0	0	48	0
Aug.	0	0	0	0	0	0	0	0	0	0
Sept.	0	0	0	0	0	0	0	0	95	
Oct.	0	0	0	0	0	0	0	0	17	
Nov.	0	80	45	12	16	0	20	29	89	
Dec.	34	75	77	75	95	0	19	144	76	
Year Total[a]	34	370	380	318	527	136	193	311	636	175
Total in liters	14,700	159,950	164,270	137,470	227,820	58,790	83,430	134,440	274,940	75,650
Cumulative Total[b]		68,650	232,920	370,390	598,210	657,000	740,430	874,870	1,149,810	1,225,460

a. millimeters

b. less 106,000 liters required for field capacity

climatic conditions (precipitation and temperature) experienced, the difference would have been 33%. This large difference indicates a need for leachate volume calculations in designs to be based on extreme as well as average values. Leachate was also collected during the summer and fall which as seen in Table 13 is rarely predicted by the water balance method.

LEACHATE QUANTITY

Test Cells #2A-2D

The experimental design called for the input of approximately 500 mm of precipitation each year into all of the cells. Average annual rainfall at the site is in excess of 1,000 mm so all of the cells were periodically covered, the cylinders with caps and 2D with nylon reinforced Hypalon®. Covers were not placed on the cells on any time schedule but whenever needed to gain as uniform an input as possible throughout the year. Generally about 100 mm of precipitation fell on the cells before they were covered for a 2-3 month period. During the final year of the project the covers were left off. Evaporation and transpiration losses were further reduced by use of the .3 m gravel layer overlying the soil cover, preventing vegetative growth and shielding the water stored on top of the soil cover from direct sunlight.

Leachate was initially collected from each test cell on the date and at the cumulative rainfall quantities in Table 14. The early appearance of leachate from 2D, indicative of some short-circuiting, also occurred in cell #1.

TABLE 14. INITIAL COLLECTION OF LEACHATE

Test Cell	Date Leachate Collected	Cumulative Precipitation[a]
2A	6-5-73	724
2B	2-13-73	588
2C	6-19-73	765
2D	9-25-72	51

a. millimeters

Figures 14 and 15 show the quantities of leachate collected from each test cell with time and with precipitation.

Test cell 2C produced very little leachate during the reporting period in comparison to 2A and 2B. A test boring in the cell did not show any free water stored in the cylinder. It is assumed that a leak developed at a welded joint near the surface of the soil cover and very little of the precipitation actually entered the refuse mass.

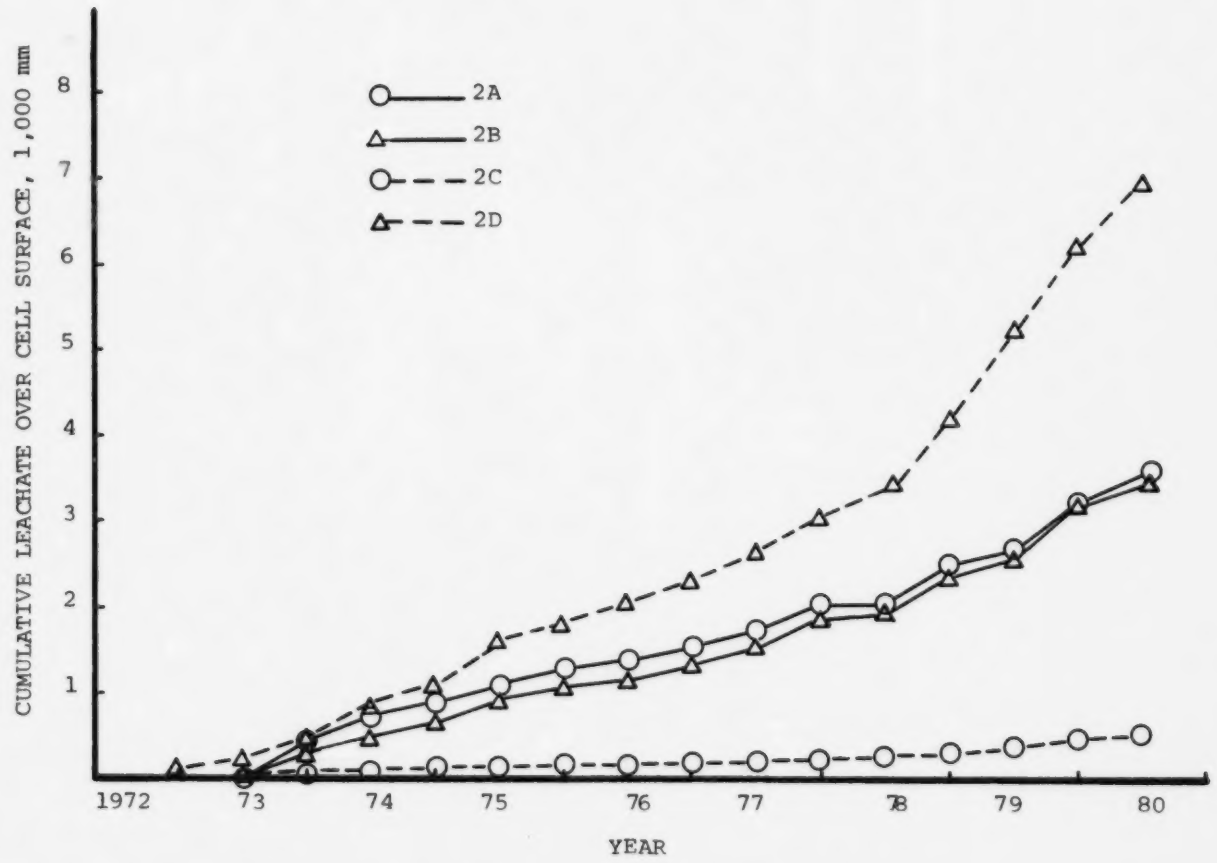


Figure 14. Cumulative leachate collected, cells 2A-2D

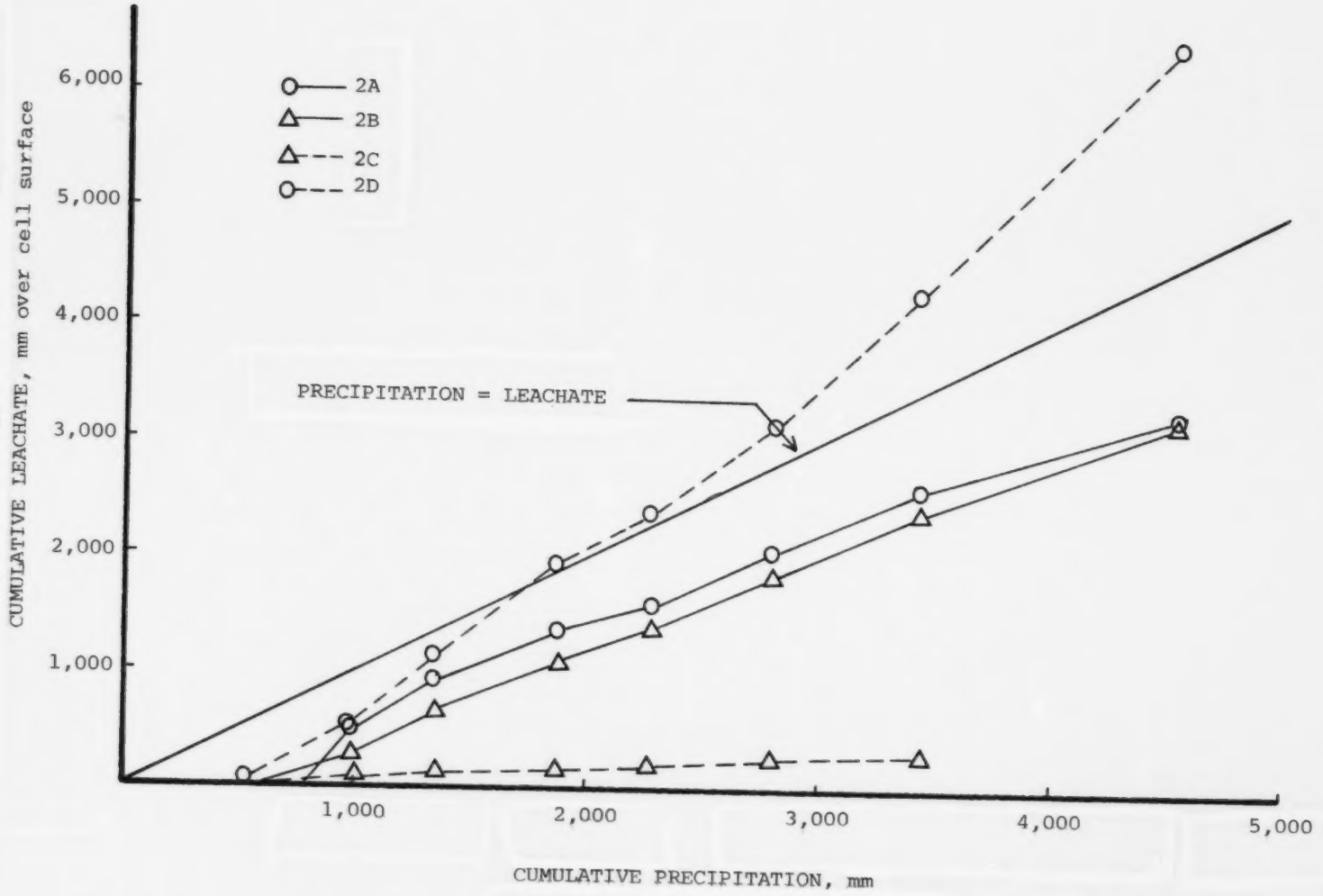


Figure 15. Leachate volume, cells 2A-2D.

The quantities of leachate collected from 2A and 2B at the end of the project period differed by only 5%. Examination of seasonal leachate flows did not show any evidence of evaporation losses for 2A and 2B. The gradual increase in the difference between moisture input and leachate collected apparent in Figure 15 was therefore due to increased storage within the refuse or cell drainage system. No free water was found in 2B during closure excavation.

Leachate collected from 2D began to exceed precipitation in mid-1975. At project completion in August 1980 leachate equivalent to 7,000 mm of precipitation had been collected, compared to an input of only 4570 mm. Potential causes of this large difference might have been leakage through the sidewalls and liner of the cell or through the Hypalon® cover that was periodically placed on the cell. During closure excavation, water was found trapped in the sand backfill around the cell, as shown in Figure 16. A rip in the liner above this level could have allowed leakage into the cell from both surface water and along seepage planes in the sidewall soil. Analysis of wet/dry season flows shows a much larger percentage of the excess leachate occurred during winter and spring months. This seems to indicate that the probable cause is seepage or surface water infiltration from the surrounding soil into the surrounding sand backfill and through the liner.

Field Capacity

The time delay between initial precipitation input and eventual steady leachate production results from water absorption by the refuse, or field capacity being reached. The quantity of water required to bring cells 2A, 2B and 2D to field capacity can be estimated graphically, as shown in Figure 17. For cell #1 the evapotranspiration from the cell surface prevents an accurate determination of the field capacity.

Graphical estimates of the additional water required to achieve field capacity for cells 2A, 2B and 2D, less 50 mm of water to bring the soil to field capacity, were 1707, 1603 and 34,230 liters respectively. This quantity of water when added to that original moisture in the refuse yields field capacity moisture contents of 53, 53 and 48% on a wet weight basis for 2A, 2B and 2D. The higher refuse density and short-circuiting of water through 2D probably accounts for its lower value, since uniform and total saturation of all the refuse in the short time period was unlikely.

Cells 1 and 2D were partially excavated during closure. Moisture determinations were made on samples removed. Refuse in Cell 2D average 58% moisture on a wet weight basis with a range from 49-63%. In cell #1 the moisture content was 55%, ranging from 43-63%. These values compare favorably with the graphical predictions. An appropriate design value for feild capacity of the refuse in sanitary landfills might therefore be 55% moisture on a wet weight basis over the long term, rather than the variable value based on density suggested by Fungaroli and Steiner[9]. A suitable allowance for moisture retention by the soil in a landfill should be added in design calculations.

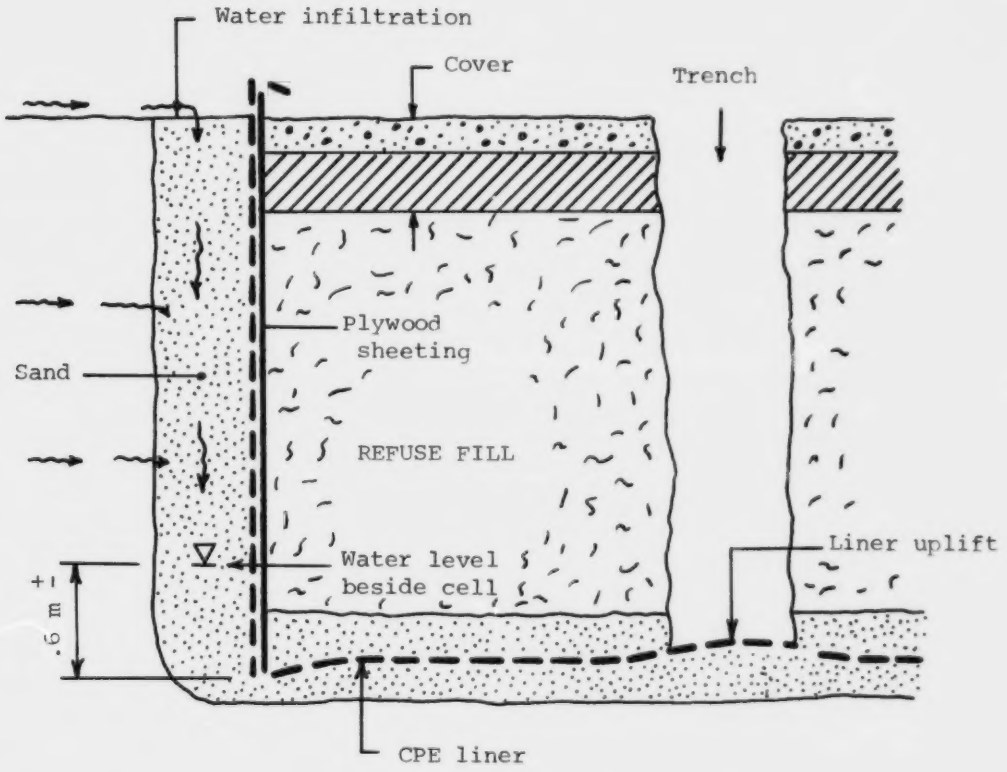


Figure 16. Liner Uplift - Cell 2D

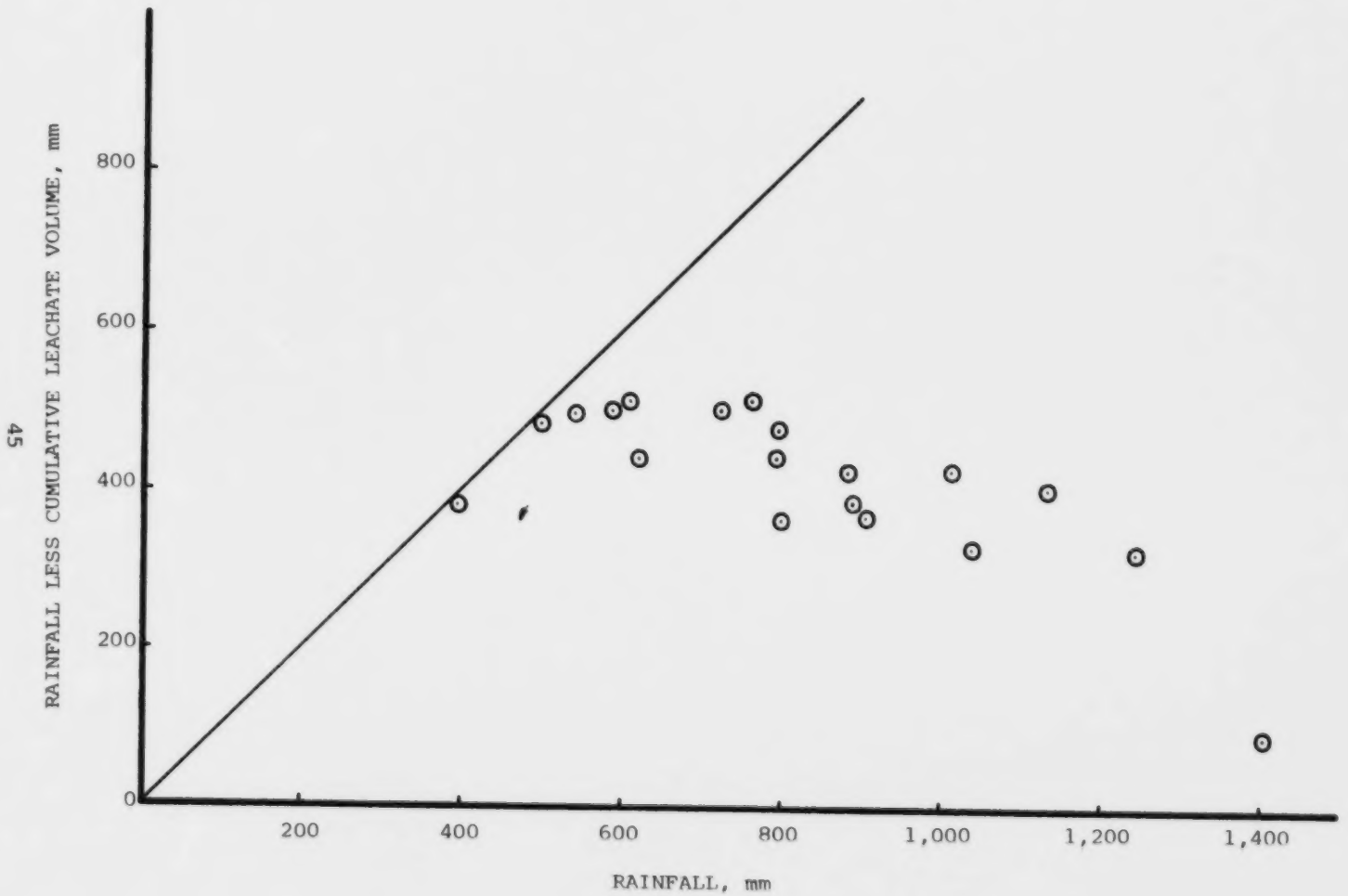


Figure 17. Field capacity determination, cell 2D.

LEACHATE CHARACTERISTICS

Leachate samples from the test cells were generally analyzed on a bi-weekly basis. The majority of the samples were analyzed at a commercial laboratory in Cincinnati. The results from Test Cell 2C are not considered in this report because of the low water flow through the cell. For comparison purposes the extensive leachate quality data has been reduced to weighted mean concentrations at the approximate time that a given ratio of cumulative leachate volume to the dry weight of refuse in the cells occurred. Weighted mean concentrations were calculated by computing the mass of the parameter for the leachate volume from sample to sample; summing these masses for the time period in which the desired leachate volume was collected and then divided by the total leachate volume during the period.

Peak Concentrations

A summary of peak concentrations and the leachate volume at which the peak occurred is presented in Table 15. Values for Cell 2C were similar to those recorded for 2A and 2B. It must be emphasized that the concentrations were recorded from relatively shallow batch cells in which there was no daily or intermediate cover soil. The results might not be indicative of concentrations that would occur under actual field conditions.

The data in Table 15 indicates a relatively small time or cumulative leachate span during which the peaks were recorded. In general this is the period during which the test cells were reaching field capacity or shortly thereafter. Apparently these peak concentrations result during the initial water contact with the refuse when the supply of leachable substances and the contact time was high.

Almost all of the peak concentrations for Cell #1 were recorded within a 6 month span, for 2A within a 2 month span beginning with the onset of leachate production. For test cell 2B the time span for peaks was somewhat longer than 2A, ranging to over 6 months. Test cell 2B began leachate production 4 months earlier than 2A and before the estimated field capacity was reached so this range might actually have coincided closely with 2A with the peak concentrations occurring during or shortly after field capacity was reached.

For test cell 2D the general time span for peaks was four months, with calcium and total hardness somewhat later. The volume of leachate collected prior to and during this time range was much greater though than for 2A and 2B and somewhat later than when sufficient precipitation had entered to satisfy estimated water requirements to reach field capacity. It did not appear that the peak concentrations for 2D occurred during the period that field capacity was reached as occurred for 2A, 2B and Cell 1. If peaks did occur during this period then the high concentrations in the leachate would had to have been either reduced by significant diluting leakage from the sides of the cell or by channelling through the cell. The latter situation would result in field capacity not actually having been achieved until somewhat after estimated water requirements had been met, possibly during the

TABLE 15. PEAK CONCENTRATIONS

Parameter	Test Cell 1 Upper Conc.[a]	Test Cell 1 Upper Leachate Vol.[b]	Test Cell 2D Conc.[a]	Test Cell 2D Leachate Vol.[b]	Test Cell 2A Conc.[a]	Test Cell 2A Leachate Vol.[b]	Test Cell 2B Conc.[a]	Test Cell 2B Leachate Vol.[b]
pH (lowest)	5.10	.01	4.6	0.5	4.4	0.4	4.4	0.5
pH (highest)	7.07	4.1	7.0	5.0	6.2	0.2	6.0	0.3
COD	37,500	0.3	41,869	0.5	57,370	0.2	61,600	0.04
BOD_5	30,000	2.1	79,120	0.9	62,560	1.0	72,220	0.7
Kjeldahl-N	700	0.4	1,413	1.2	1,560	0.2	1,897	0.3
Ammonia-N	552	0.3	947	0.5	1,035	0.5	1,185	0.3
Orthophosphate	61	0.04	82	0.4	390	0.02	185	0.1
Sulfate	1,160	0.3	1,280	0.5	2,215	2.2	2,775	1.9
Alkalinity	8,870	0.3	8,963	0.7	11,535	0.2	13,880	0.01
Acidity	3,620	0.3	5,057	0.7	6,720	0.06	6,843	0.2
Conductivity	12,200	0.2	16,000	1.0	17,000	0.2	18,000	0.2
Total Solids	23,600	0.3	36,252	0.4	46,484	0.2	45,628	0.2
Sodium	1,040	0.4	1,375	0.4	1,900	0.2	1,700	0.2
Potassium	1,950	0.7	1,893	0.5	2,225	0.1	2,939	0.3
Chloride	1,749	0.6	2,940	1.0	3,558	0.2	2,450	1.3
Iron	616	0.9	1,492	2.4	1,547	0.2	2,902	0.04
Magnesium	374	0.2	411	0.5	486	0.2	617	0.3
Manganese	184	0.04	58	0.4	109	0.02	115	0.04
Calcium	2,360	0.9	2,300	0.6	2,470	0.2	4,000	0.04
Zinc	104	0.2	67	0.3	150	0.1	360	0.1
Hardness	7,500	0.3	6,713	1.9	7,067	0.06	10,575	0.04

a. Concentration in mg/l except for pH and Conductivity (micromhos/cm)

b. Cumulative Leachate Volume - liters per dry kilogram of refuse

time and leachate volume range when peak concentrations were recorded. Dilution was indicated by the lower magnitude of almost all of the peak concentrations of 2D as compared to 2A and 2B.

Peak concentrations recorded in leachate samples of the parameters listed in the EPA interim primary drinking water standards together with copper and phenols are presented in Table 16. These peak concentrations were recorded over a wide time span, with very few occurring during the period field capacity was being recorded.

It is notable that for all but silver and flouride these peaks exceeded the drinking water standards. Thus even the leachate from municipal trash such as used in these studies has the potential for causing the maximum contaminant levels in ground water specified by the landfill criteria[10] under Subtitle D of RCRA to be exceeded. For both mercury and cadmium the peaks were generally in excess of 100 times the interim primary drinking water standards. The percentage of samples in which the leachate concentration exceeded these standards is shown in Table 17. The high frequency of exceedence for mercury is in part due to the low standard of .002 mg/l.

Concentration Trends

The concentration history and mass removal curves for selected parameters for the four test cells are presented in Figures 18-48. The concentration or cumulative mass removal has been plotted against the cumulative leachate volume rather than time since the leachate concentration trends and subsequent mass removals are more leachate volume than time related. Leachate volume and mass removal data are also normalized by dividing by the dry weight of the refuse to account for the different sizes of the cells.

pH

Leachate pH for all the cells generally remained in the 5.0-6.0 range throughout the study period as shown in Figure 18. Values for 2D were above the other cells possibly due to the diluting side wall leakage. The pH did not rise to the neutral range of 6.6-7.4 optimal for vigorous anaerobic activity. There was some short term dependence of pH on high leachate production. Short duration increases in pH generally followed periods of heavy precipitation indicating a dilution of the buffering system.

Total Solids

Analyses for total, dissolved, volatile and suspended solids were performed on leachate samples. Generally the total and dissolved values were numerically close with suspended solids usually less than 200 mg/l. The weighted mean concentration history and mass removal curves are shown in Figures 19-20. Values for all cells peaked during the period field capacity was being achieved. Thereafter concentrations gradually declined to less than 3,000 mg/l after collection of 5 liters of leachate per kg of dry refuse.

TABLE 16. PEAK CONCENTRATIONS[a]

Parameter	Cell #1 - Conc.	2A - Conc.	2B - Conc.	2C - Conc.	2D - Conc.	Standard [b]
Arsenic	.125	.417	.414	.352	.381	.05
Barium	1.605	2.440	1.440	2.48	4.29	1.0
Cadmium	.790	1.45	1.12	2.67	1.47	.01
Chromium	.063	.139	.240	.338	.293	.05
Fluoride	2.84	.652	.87	.418	.29	1.4-2.4
Lead	1.144	.361	3.0	.63	.236	.05
Mercury	.279	.376	.208	.240	.339	.002
Nitrite & Nitrate	17.3	33.8	28.3	183	32.4	10[c]
Selenium	.047	.264	.090	.103	.185	.01
Silver	.10	.013	.022	.017	.011	.05
Copper	2.80	6.68	1.27	1.41	5.05	1.0[d]
Phenols	4.6	9.3	9.6	8.3	6.7	.001[d]

a. All values in mg/l

b. Interim primary drinking water standards, USEPA; except copper and phenols

c. Nitrate only

d. 1962 PHS Standards

TABLE 17. FREQUENCY OF LEACHATE SAMPLE CONCENTRATIONS EXCEEDING INTERIM PRIMARY DRINKING WATER STANDARDS

Parameter	Test Cell				
	#1 - Upper[a]	2A	2B	2C	2D
Arsenic	6	14	20	22	7
Barium	3	7	7	9	4
Cadmium	32	22	27	21	26
Chromium	4	35	37	62	34
Fluoride	6	0	0	0	0
Lead	36	33	38	36	44
Mercury	71	63	57	62	60
Selenium	32	25	30	17	24
Silver	9	0	0	0	0

a. Percent (%) of the total number of analyses that the concentration exceeded the standard.

Plots of concentration of individual samples versus leachate volume over wide ranges in volume produced scatter diagrams, indicating no correlation between the concentration and the amount of leachate volume collected between samples. The only notable leachate volume related trend is that depicted in Figure 19, the gradual decline in concentration with cumulative leachate.

The concentration history plots are quite similar for all the test cells. Lower initial and peak values for the large cells 1 and 2D were recorded, perhaps due to short-circuiting of water through the refuse mass. After 1 liter of leachate per kilogram of refuse had been collected the concentrations for all the cells ranged within 5 g/l of each other. The cumulative mass removal curves closely parallel one another for the entire study period. The primary difference in the quantity of mass removal per unit of refuse weight is due to the lower initial concentrations in the larger cells prior to and during the period field capacity was being achieved. Total mass removal after 4.5 l/kg of dry refuse of leachate ranged from 3.7-5.3% of the total refuse mass.

COD-BOD

The COD was determined on all leachate samples from the five cells. BOD analyses were run periodically but early results were highly variable and not considered reliable. The weighted mean concentrations of COD with leachate volume are shown in Figure 21 and the mass removals per unit weight of dry refuse in Figure 22.

The concentration history curves for cells 2A and 2B coincide reasonably well. Final recorded COD concentration values for the small cells ranged from 5,000-8,000 mg/l indicating incomplete stablization of the refuse. Values for the larger cells, 2D and 1, were in the 200-600 mg/l range.

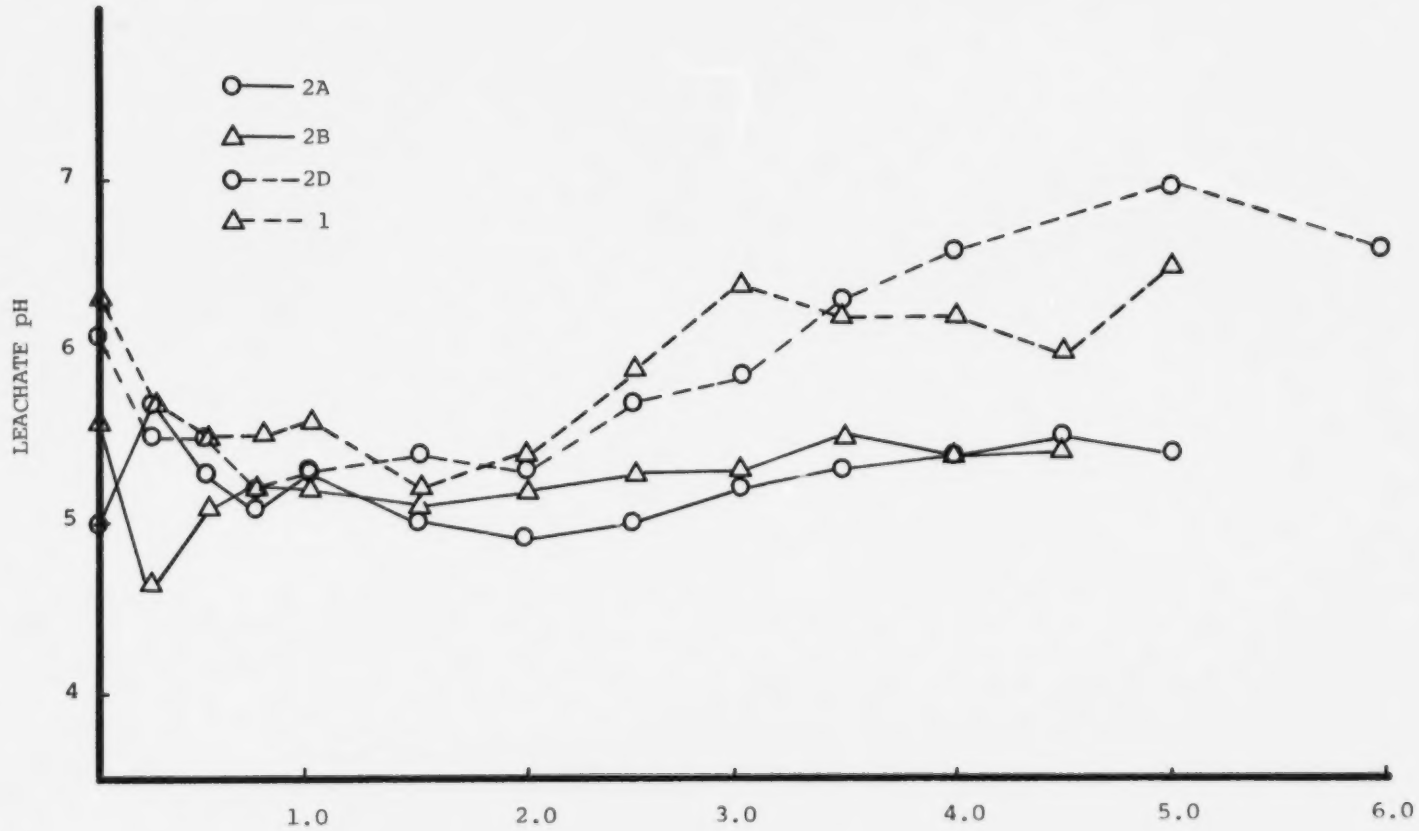


Figure 18. Leachate pH.

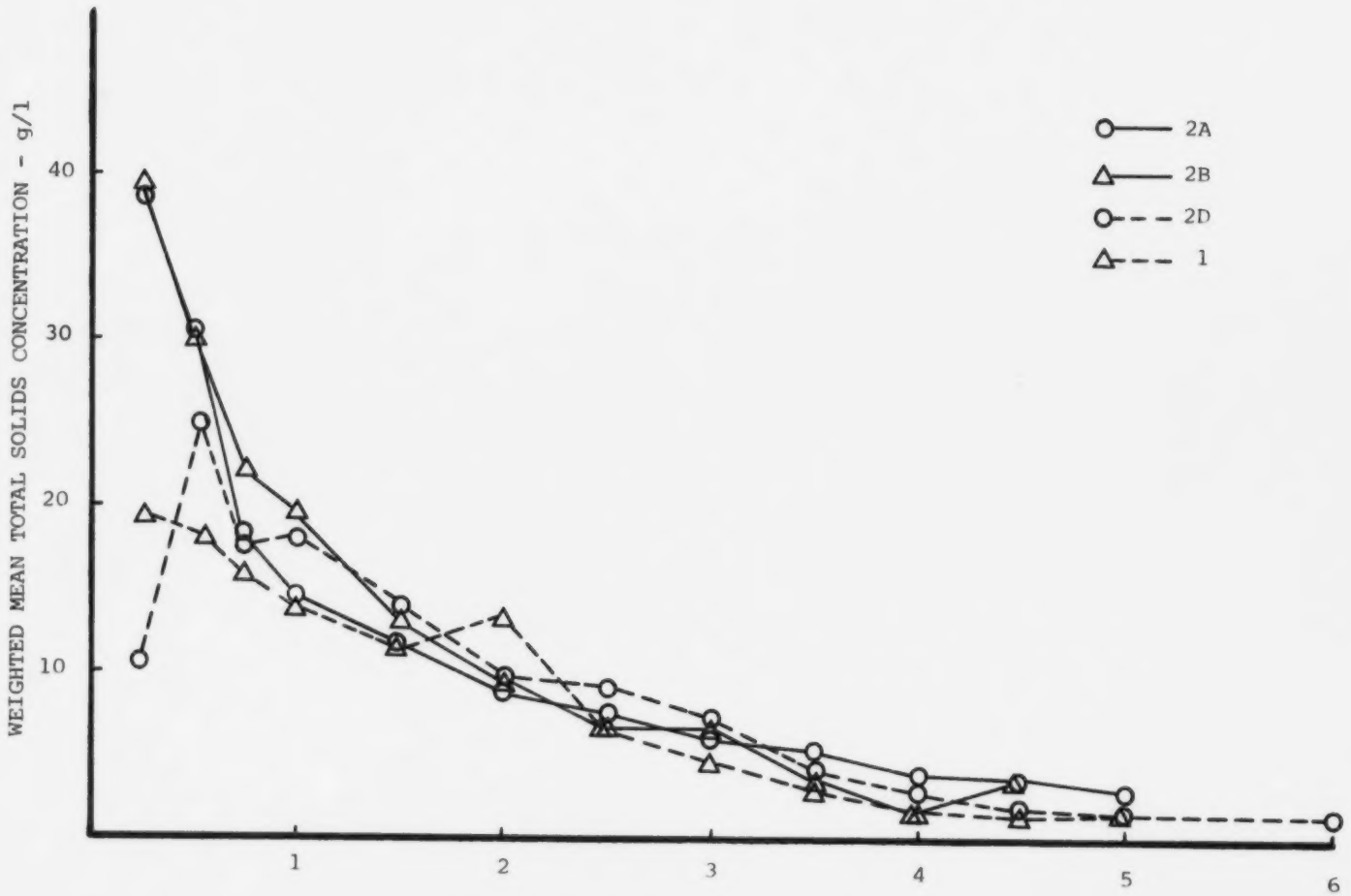


Figure 19. Total solids concentration history.

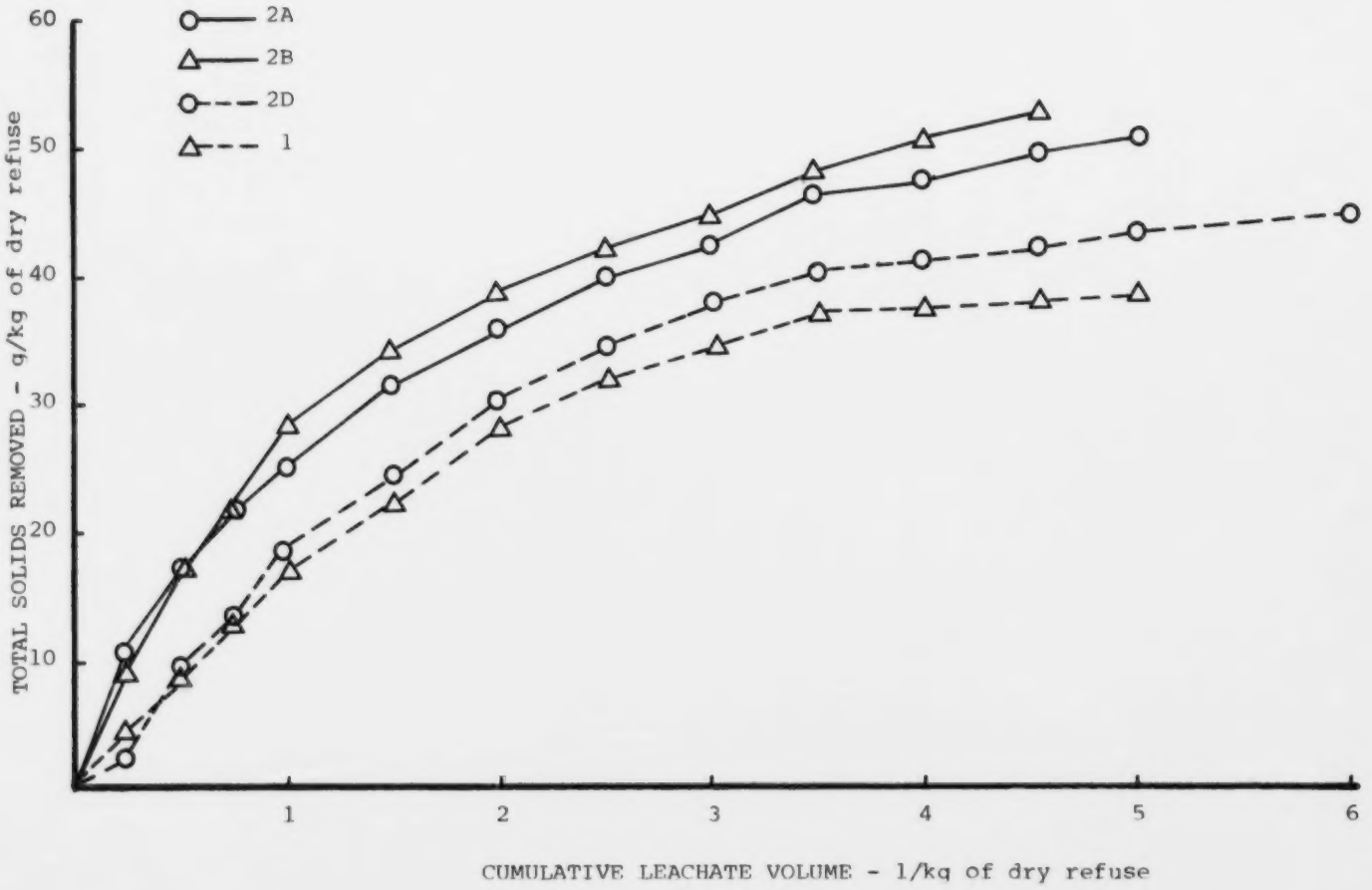


Figure 20. Total solids mass removal.

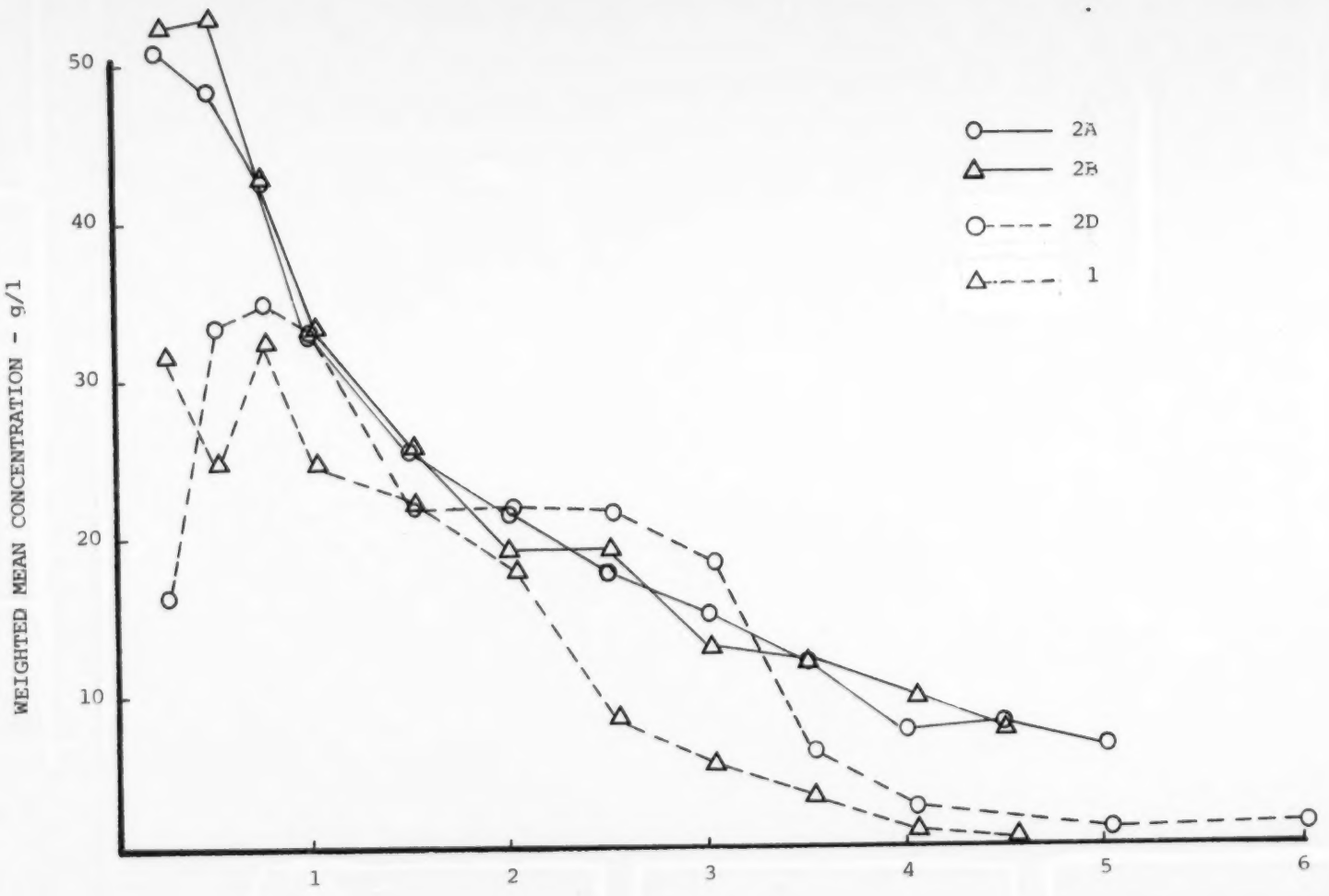


Figure 21. COD concentration history.

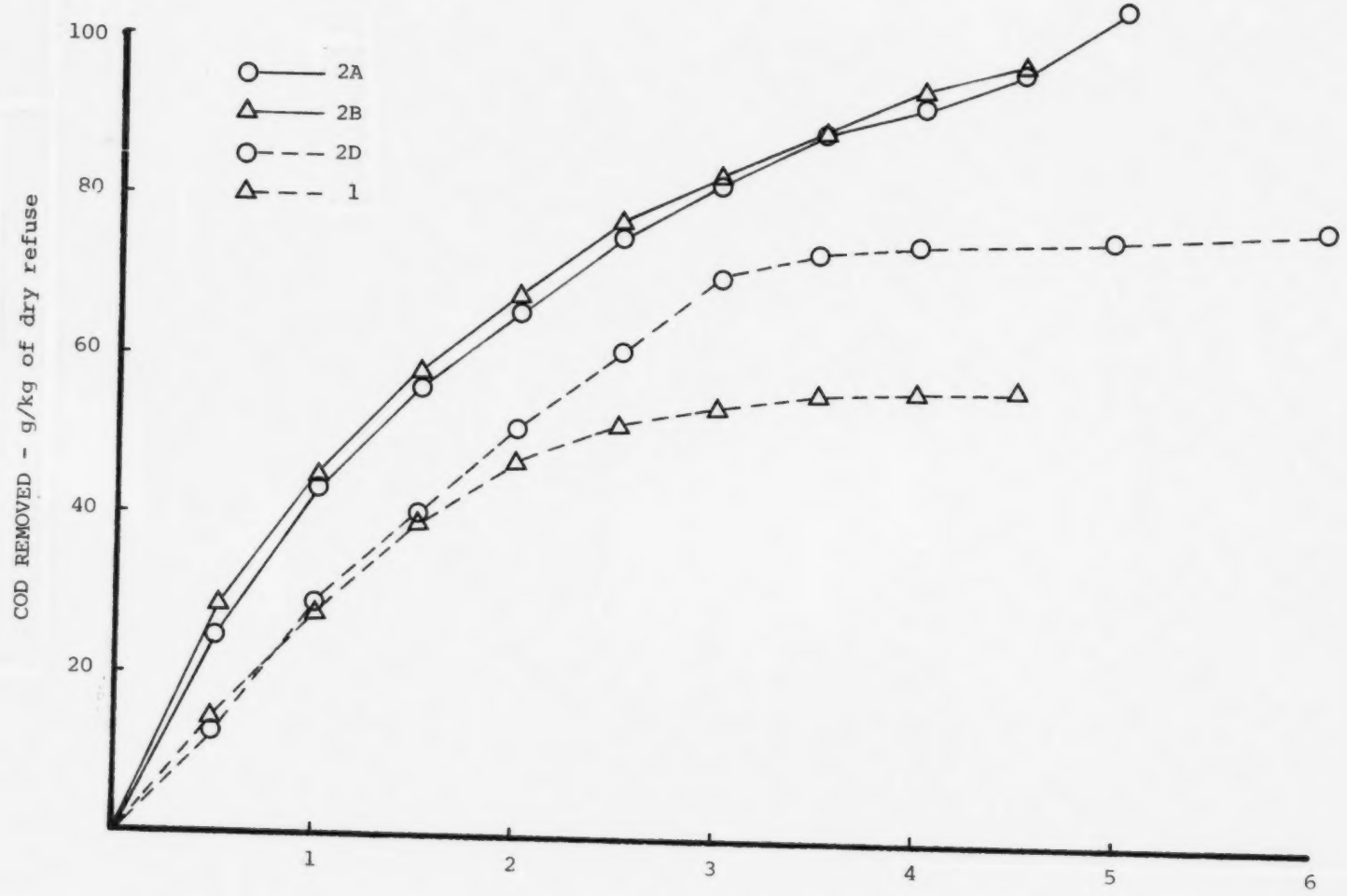


Figure 22. COD mass removal.

Analysis of squeezings from the refuse in Cell #1 at closure showed an increase in the COD from 2700 mg/l at a depth of 1.2 m to 4500 mg/l at 1.8 m and to 9400 mg/l at 2.4 m. There was very little increase in the COD with depth in the refuse from 2B, indicating more uniform leaching of the refuse. A COD increase with depth was recorded at one location in 2D and a decrease at another. The point where the decrease was recorded was much closer to the edge of the cell and at approximately the same level as the water that was found trapped outside the CPE liner (Figure 16). Leakage through the liner into the edges of the cell refuse at this level could have caused the lower value of COD.

Cumulative COD expressed as mass removed from 2A and 2B were similar throughout the study period just as the concentrations were. While the slopes of the curves (Figure 22) were tending to decrease, the high COD concentrations still being recorded indicated incomplete refuse stabilization. Cumulative COD removals from the larger cells, 2D and 1, were only 50-80% of that from the small scale cells. Analysis of refuse solids from Cells 1, 2B and 2D at closure did not indicate any substantial difference in remaining COD values. This would indicate that diluting leakage and less refuse contact due to short-circuiting of water through the larger cells, resulting in lower concentrations, might be part of the cause of the mass removal difference between the small and large cells.

An average COD of 787 g/kg of dry refuse was measured in refuse samples taken during construction of Cell #1. Samples from Cells 2A-2D were inadvertently destroyed. Refuse samples taken during closure excavation into Cells 1, 2B and 2D had an even higher average COD value that ranged from 956-1058 g/kg. As a result of these higher residual values the measurements were not meaningful in comparing the measured change with the mass removed by leaching.

Sulfate

The sulfate concentration histories and mass removals are plotted in Figures 23 and 24. Peak concentrations were recorded during the period field capacity was reached. Peaks for 2A and 2B were 25% higher than those recorded for cells 1 and 2D. After 3 liters of leachate per kilogram of dry refuse had been collected the sulfate concentrations had dropped to 50-150 mg/l, only 5-15% of the peak concentrations.

Cumulative mass removal curves for all four cells were quite similar. Values for cells 1 and 2D were slightly lower than 2A and 2B. Sulfate analysis of refuse placed in cell 1 averaged 3.78 g/kg. Measured removal was 1.20 g/kg or 32% of the original value. Residual sulfate in cell 1 refuse averaged 6.9 g/kg, almost twice the original value.

Nitrogen

Leachate samples were generally analyzed for Kjeldahl and ammonia nitrogen and occasionally for nitrate and nitrite. Concentration histories and mass removals are shown in Figures 25-28. Similarly timed peaks were recorded for all cells but peak values of Kjeldahl nitrogen for cell 1 were only

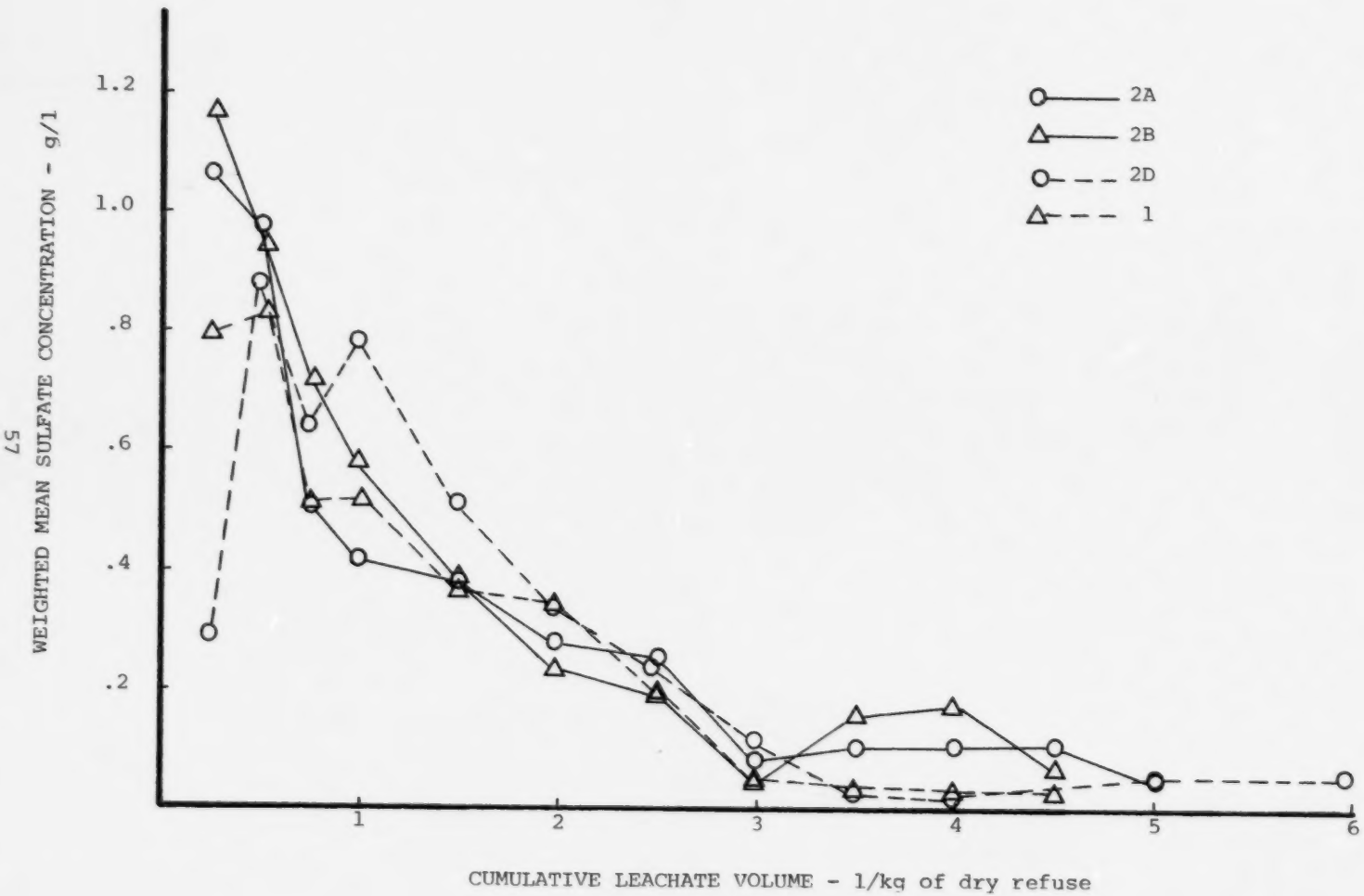


Figure 23. Sulfate concentration history.

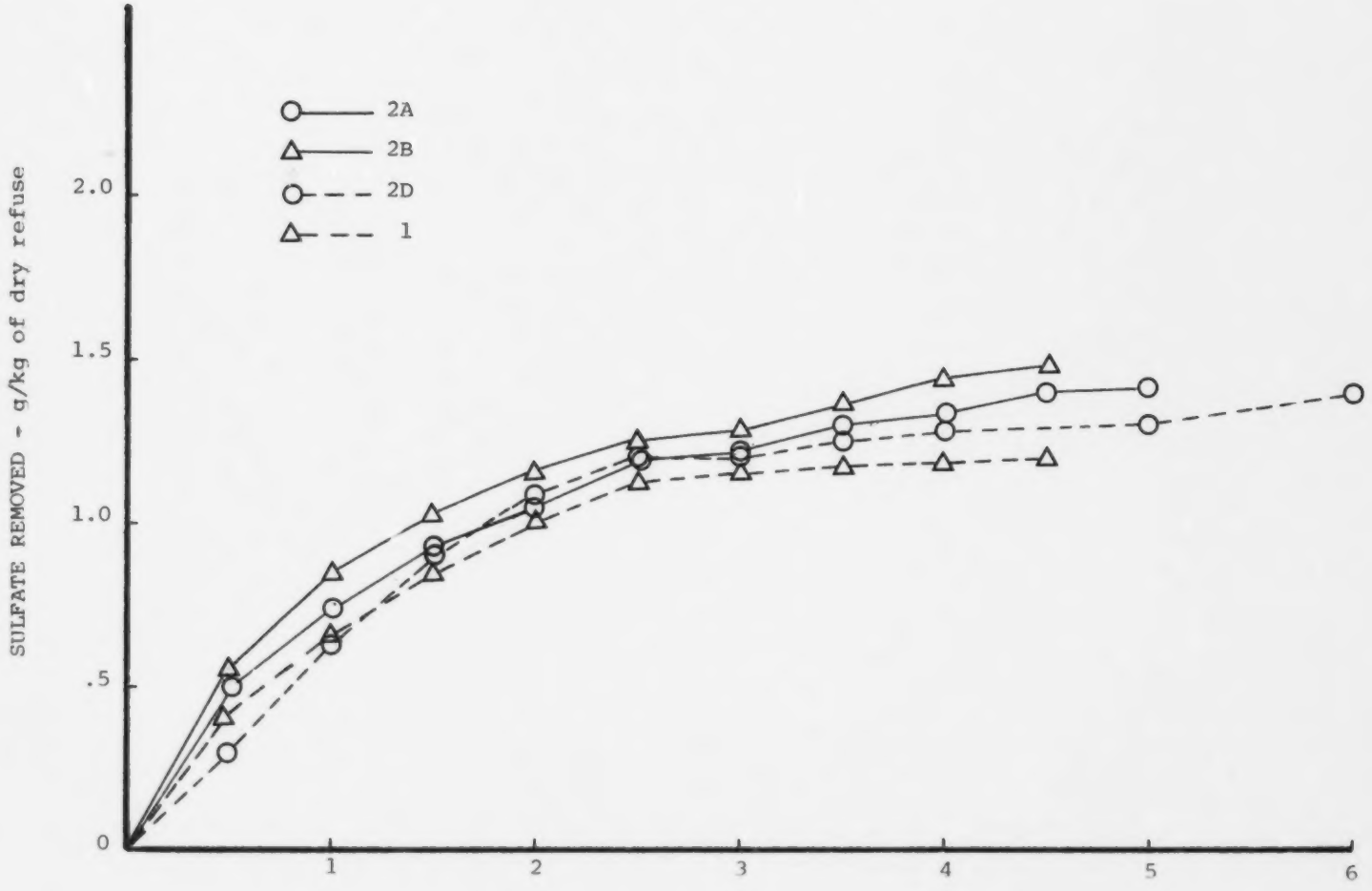


Figure 24. Sulfate mass removal.

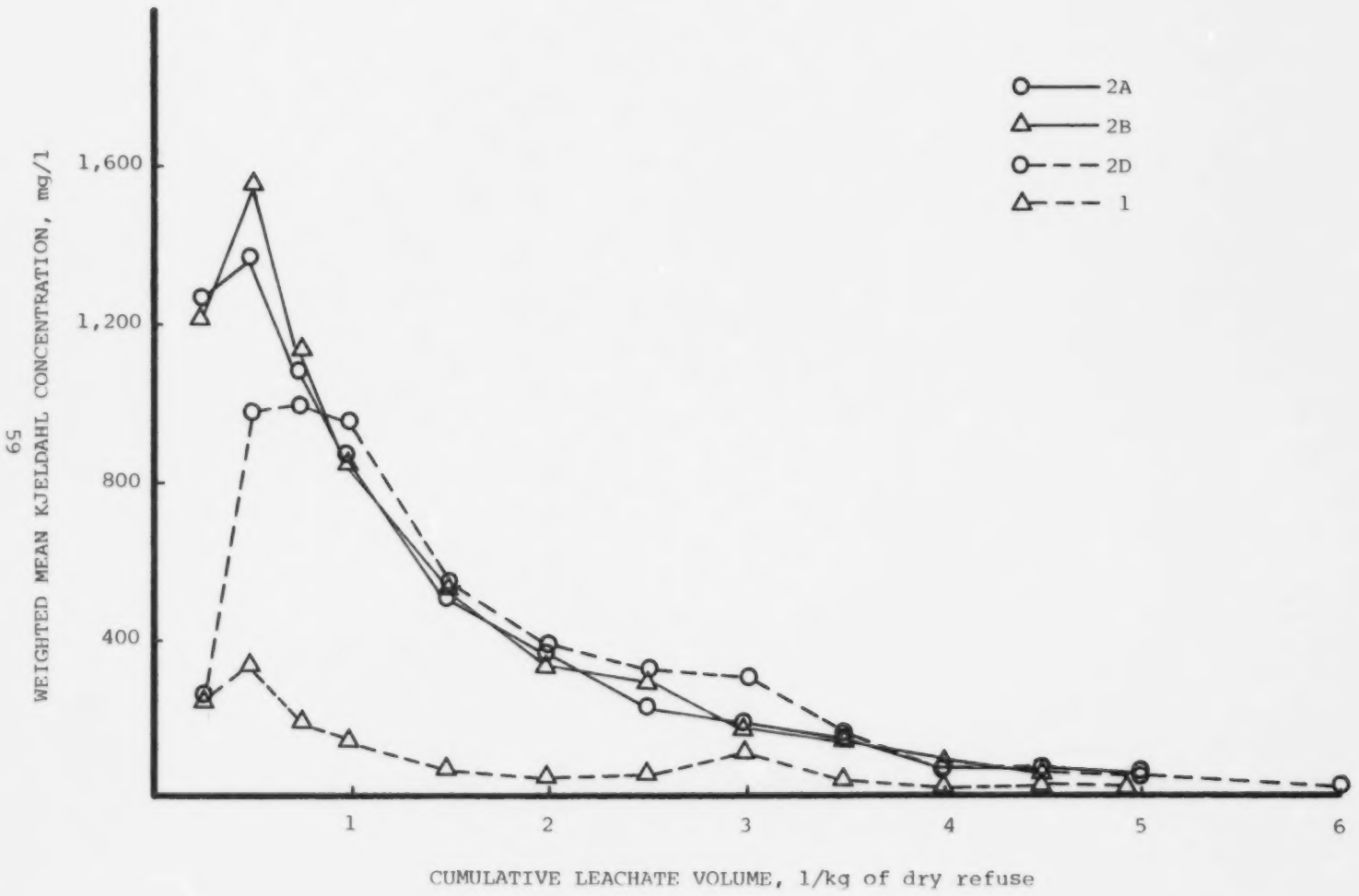


Figure 25. Kjeldahl-N concentration history.

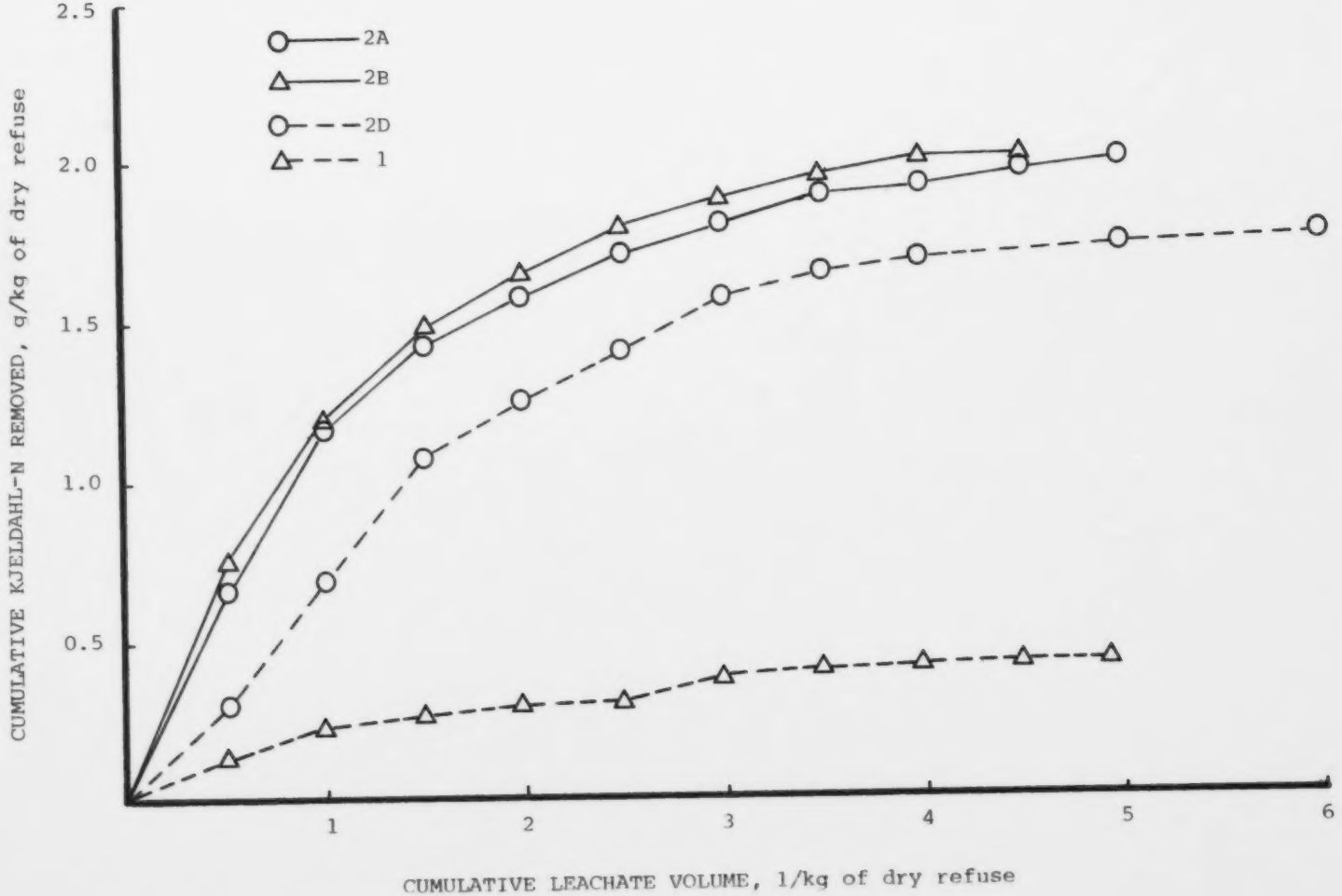


Figure 26. Kjeldahl-N mass removal.

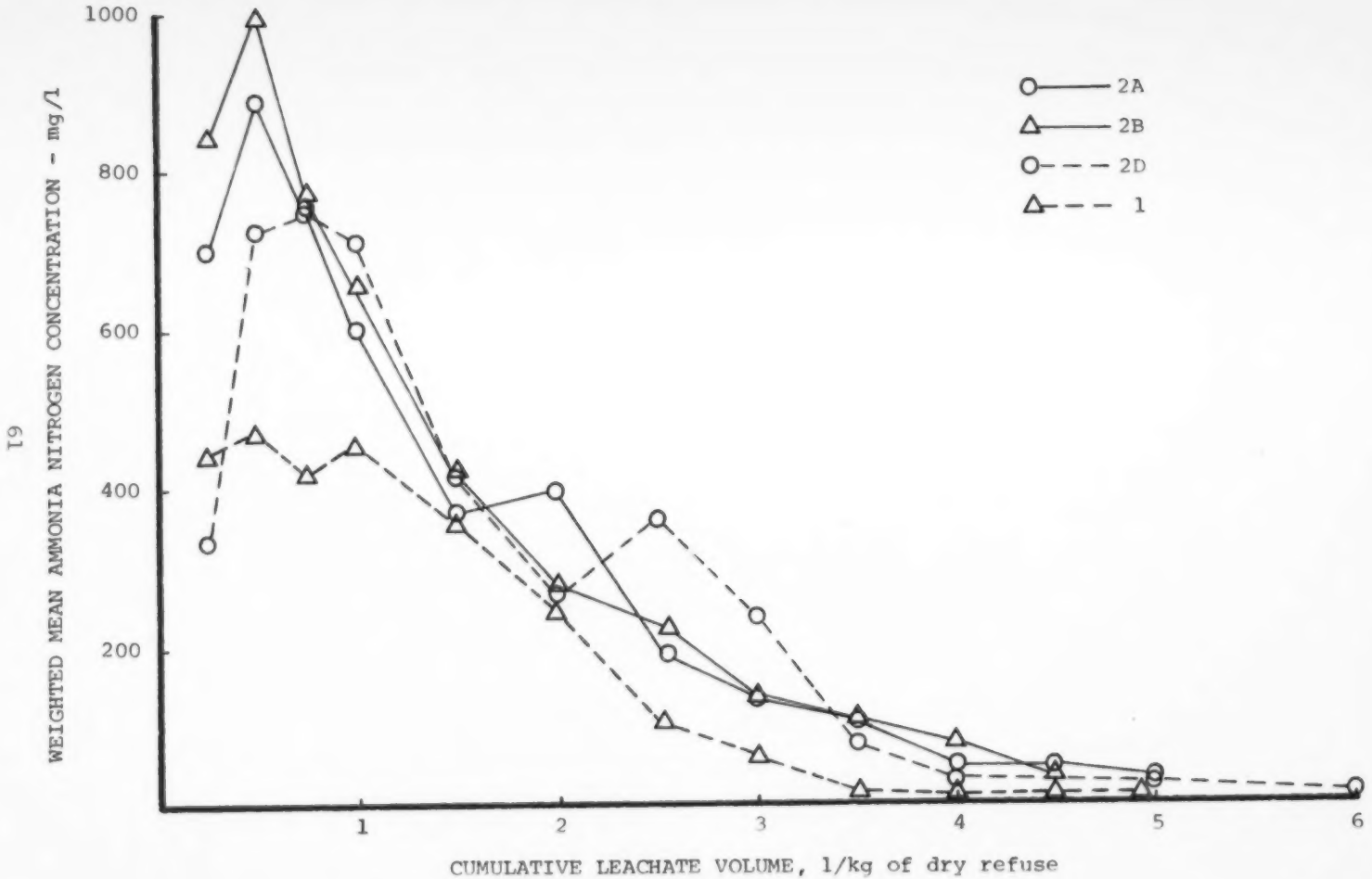


Figure 27. Ammonia-N concentration history

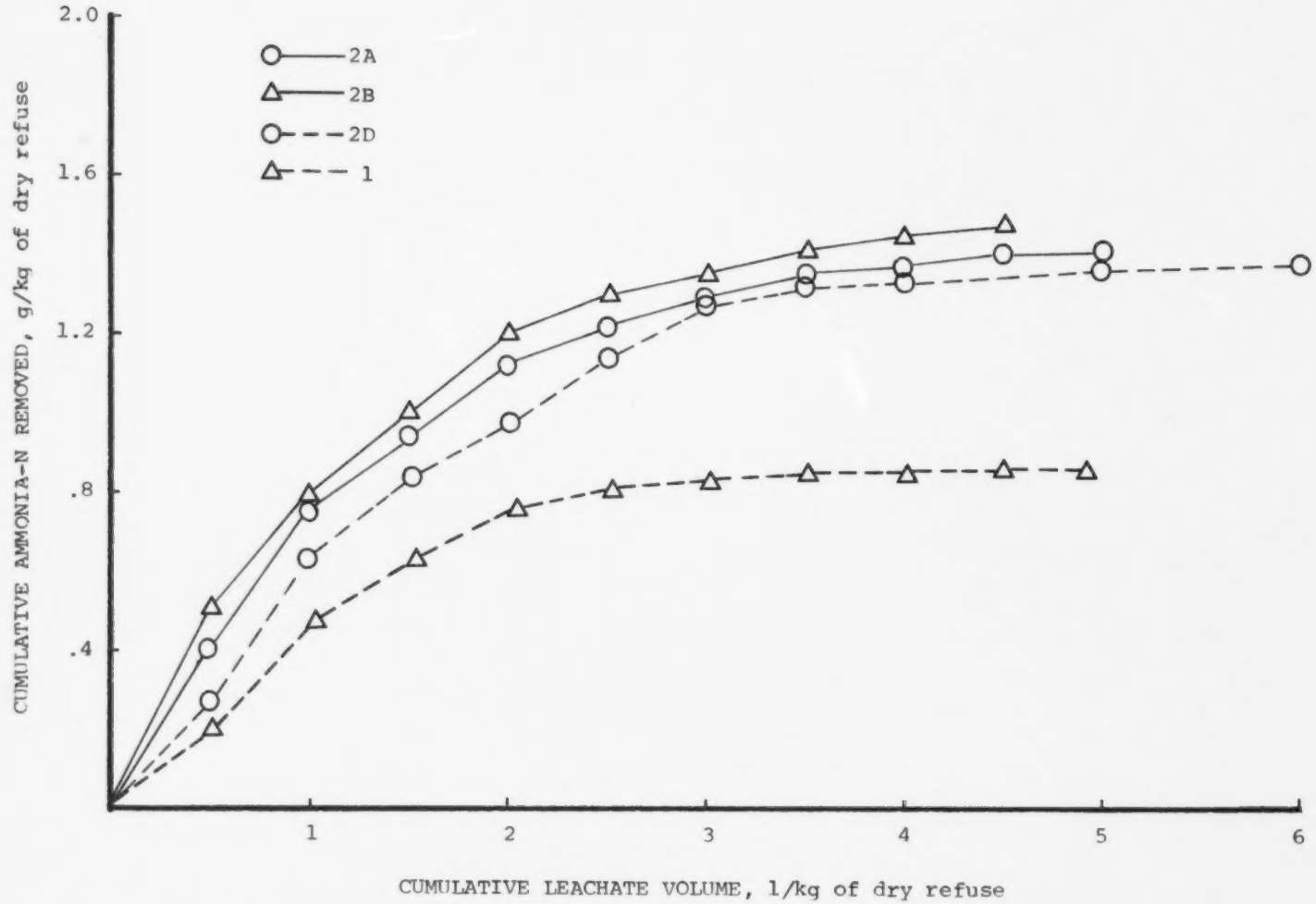


Figure 28. Ammonia-N mass removal

24% of that recorded in 2A and 2B. The ammonia nitrogen peak in cell 1 was less than half that recorded in 2A and 2B. Insufficient nitrate-nitrite analyses were done to determine whether total nitrogen removal was similar. Concentration values for both ammonia and Kjeldahl nitrogen in the leachate from cell 1 remained below the values recorded in cells 2A-2D throughout the study, perhaps indicating less leachable nitrogen available in the refuse in cell 1 or a greater loss in gaseous form.

Mass removals of Kjeldahl and ammonia nitrogen were similar for both 2A and 2B. Cumulative removal from 2D was only about 10% less than from 2A and 2B. Kjeldahl nitrogen removal from cell 1 was only 20% of that from 2A and 2B per unit weight of dry refuse.

Phosphate

Analyses were performed on leachate samples for both ortho and total phosphate. Graphs of orthophosphate concentrations and mass removals for the four test cells are shown in Figures 29 and 30. Peak values varied widely, ranging from over 200 mg/l in cell 2A to 35 mg/l in cell 1. Concentrations for both 2A and 2B remained relatively constant throughout the study whereas for 2D and 1 the concentrations trended downward with cumulative leachate volume to less than 5 mg/l at the conclusion of the research program.

Cumulative mass removal curves for the cells were quite different due to the concentration variations. Removals at 4.5 liters of leachate per kilogram of dry refuse ranged from .066 to .178 g/kg of dry refuse. The difference was most notable for 2A and 2B, the identical small scale cells. Residual total phosphate measured at 16 locations in cells 1, 2B, 2C and 2D ranged from .015-.076 g/kg of dry refuse as compared to an original value of 4.3 g/kg.

Chloride

Figures 31 and 32 show the weighted mean concentration histories and cumulative mass removals of chloride for the four test cells. Peak concentrations in all cells were recorded during the period field capacity was being reached. As occurred for other parameters, the peaks for cells 1 and 2D were lower than for 2A and 2B. The concentration trends for all cells were similar but at one point varied by more than 600 mg/l. After the collection of leachate totaling from 1.8-2.3 l/kg the concentration of chloride dropped below the recommended drinking water standard of 500 mg/l. Chloride values in the water squeezed from the refuse at closure ranged from 10.1-96.1 mg/l.

Cumulative mass removals of chloride were similar for all test cells, ranging from 2.0-2.5 g/kg of dry refuse at a cumulative leachate volume of 4.5 l/kg. The flat slope of the curves, low residual chloride within the water in the cells, and low leachate concentrations all indicate almost complete removal of readily soluble chloride from the refuse. Residual chloride analyses at closure ranged from 18-588 g/kg of dry refuse, with an average of 159 g/kg. Therefore continued chloride release at low levels

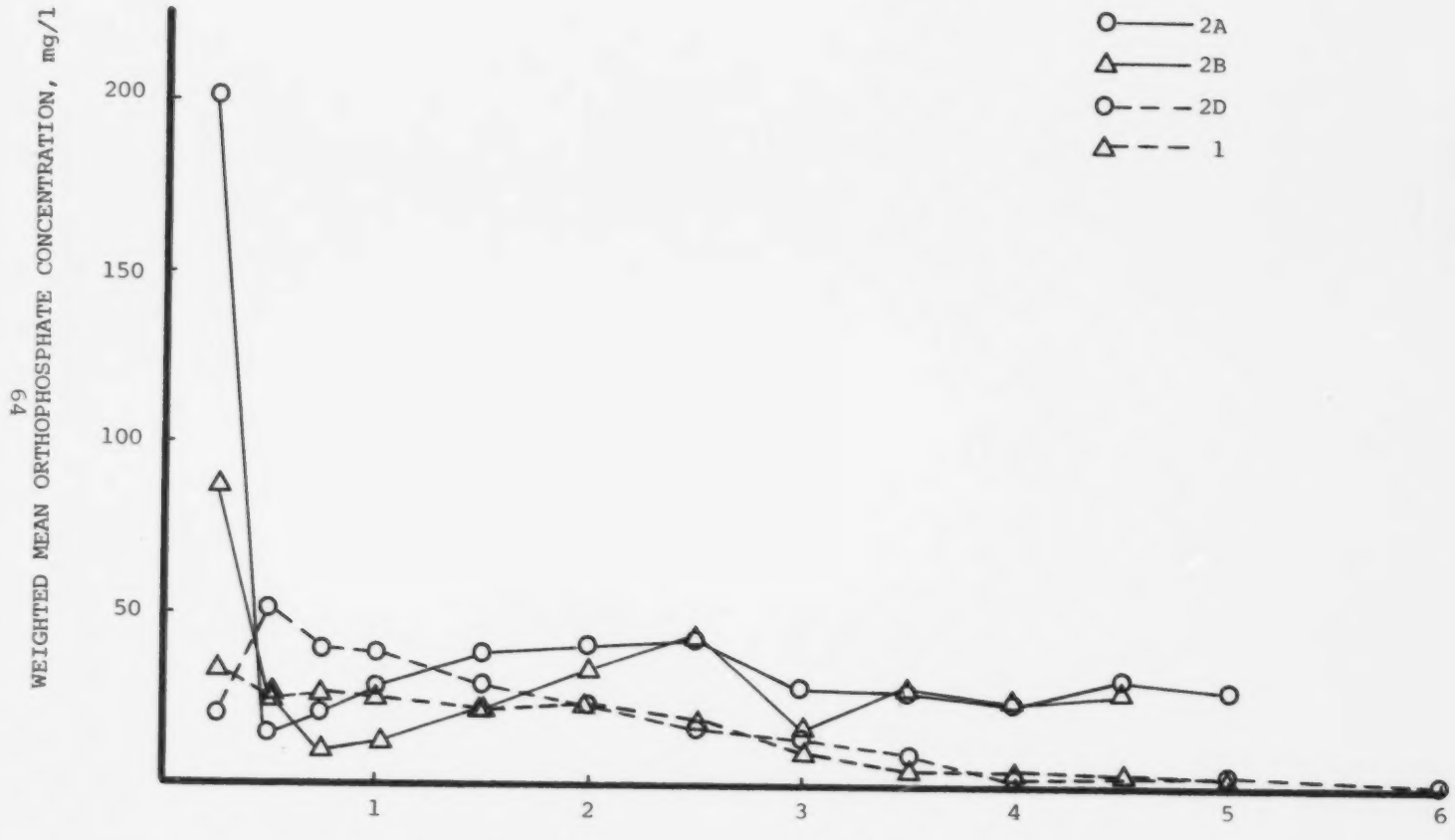


Figure 29. Orthophosphate concentration history.

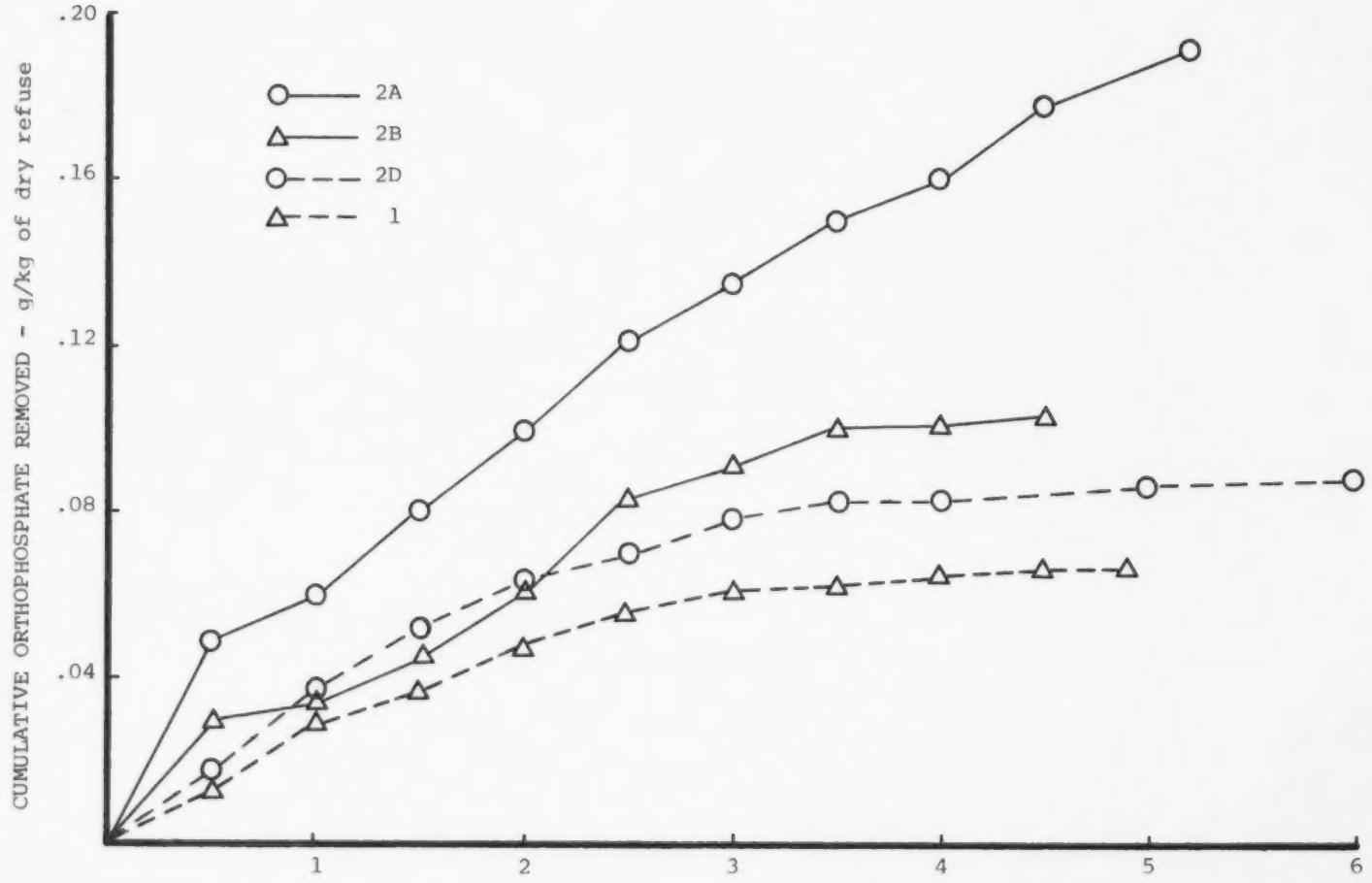


Figure 30. Orthophosphate mass removal.

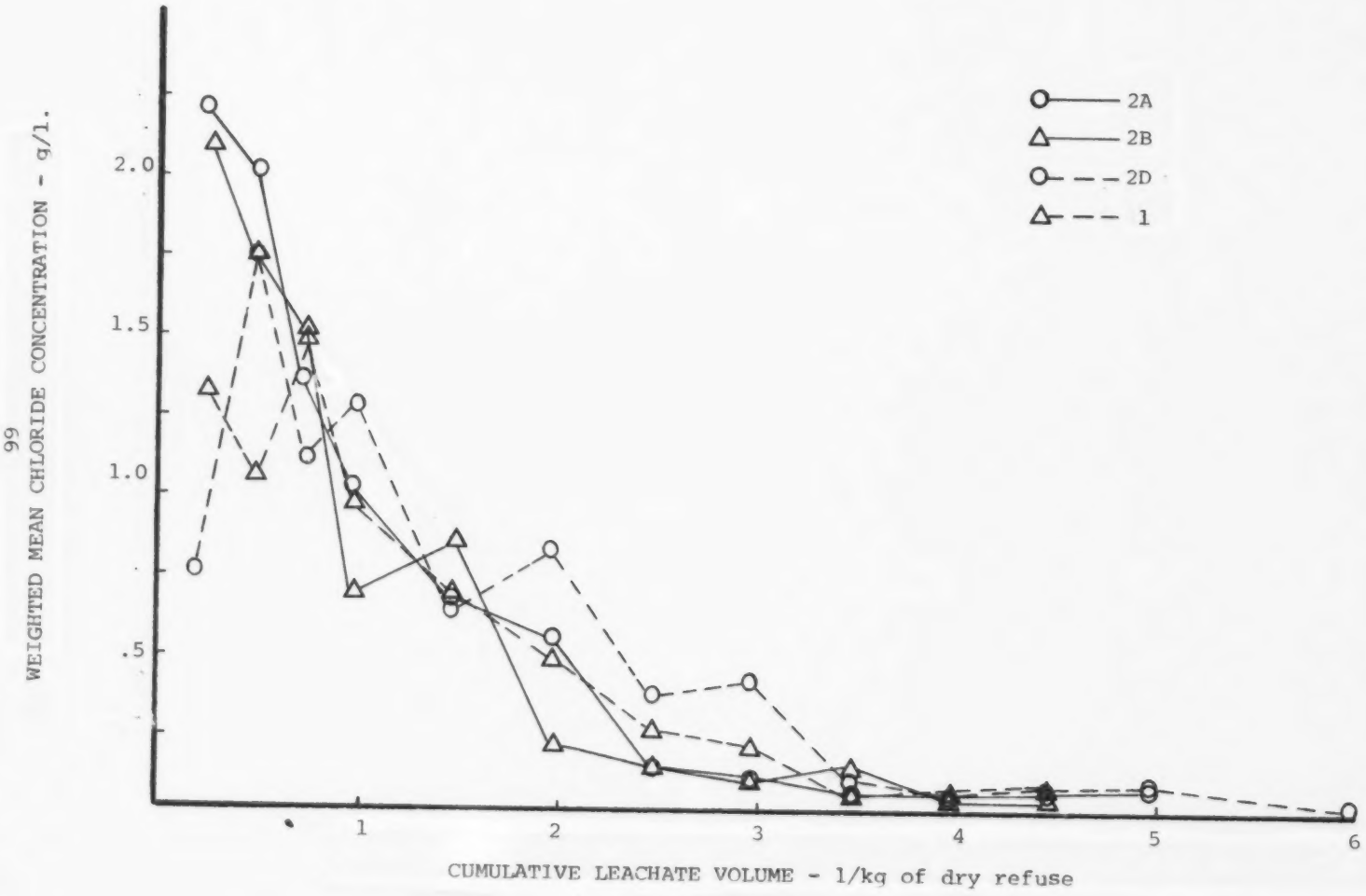


Figure 31. Chloride concentration history.

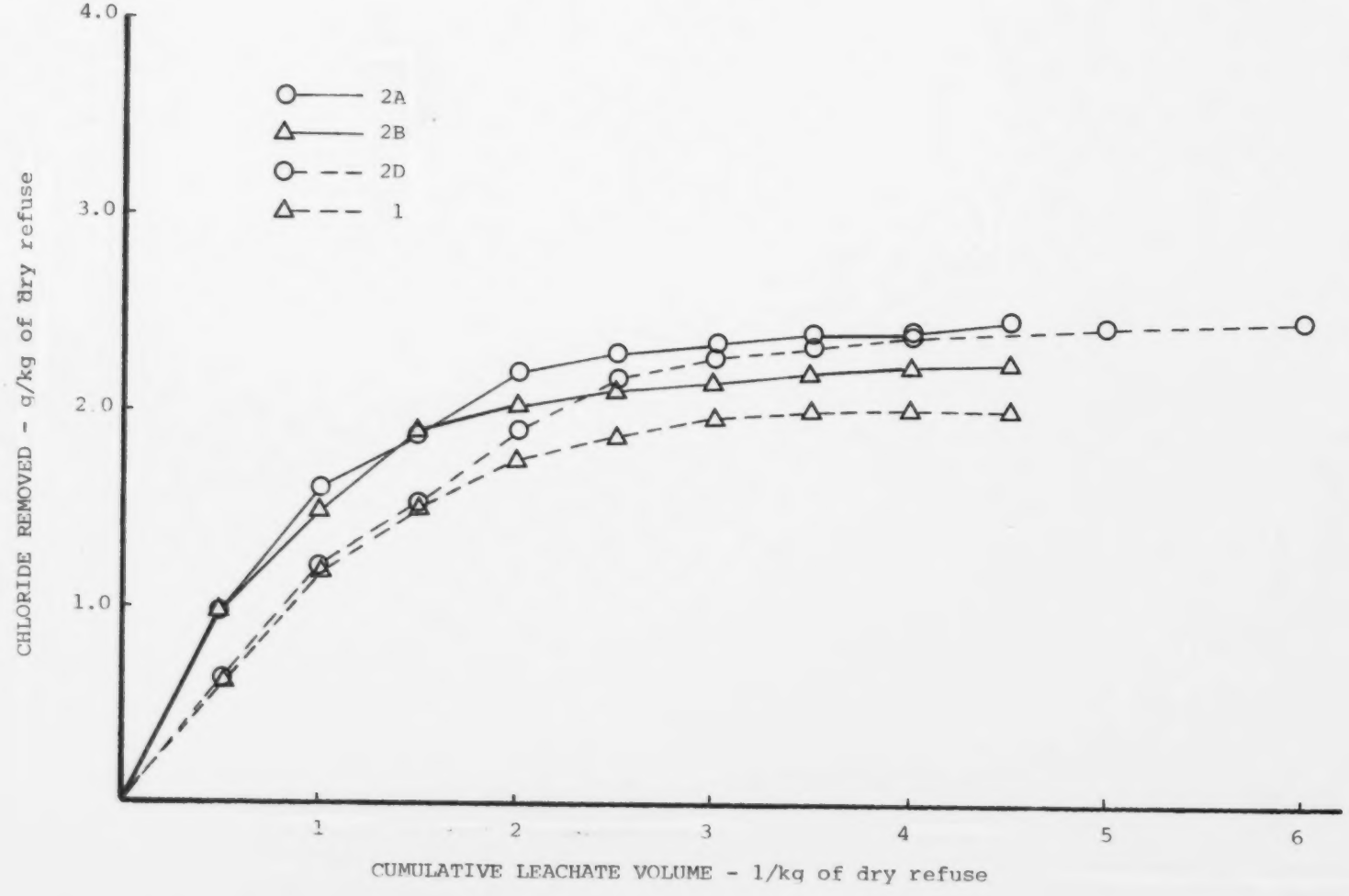


Figure 32. Chloride mass removal.

could be anticipated as decomposition continued.

Potassium and Sodium

The weighted mean leachate concentrations and mass removals of potassium and sodium from the four test cells are shown in Figures 33-36. Again the peak values in the two large scale cells, 1 and 2D, were less than that recorded in cells 2A and 2B. All of the peaks were during the period field capacity was being reached. After cumulative leachate of 1.5 l/kg of dry refuse the potassium concentrations tended to be similar for all cells for the remainder of the study. Concentration values were similar for both ions.

Mass removals at closure ranged from 1.25-2.0 g/kg of dry refuse. Removal rates at the end of the study were very low, indicating little readily soluble sodium or potassium remaining. Residual solids analyses of sodium ranged from .16-2.25 g/kg and from .017-.113 g/kg of dry refuse for potassium. Analysis of the refuse placed in cell 1 showed similar amounts of potassium and sodium initially present, therefore more complete removal of potassium took place although the removal rate was similar to that of sodium.

Hardness

Hardness concentration history and mass removal plots for the four cells are shown in Figures 37 and 38. Except for a wide range in early peak values, hardness concentrations were quite similar for all four cells. The concentrations did not decline as rapidly after the early peaks as for the monovalent cations, sodium and potassium. After 4.5 liters of leachate per kilogram of dry refuse had been collected hardness concentrations remained in the 600-1000 mg/l range or about 15% of the peak values recorded, whereas sodium and potassium concentrations had dropped to 2-3% of initial peak values. Much of this slower hardness removal appears to be due to the very slow drop in iron concentrations.

Mass removal rates were very similar with the difference in final values primarily resulting from the variation in initial peak values. Total removals ranged from 11.3-13.4 g/kg of dry refuse. This represents less than half of the 30 g/kg measured in the refuse placed in cell 1. Residuals analysis at closure showed a range from .06-.61 g/kg of hardness remaining, however the continued high concentrations of iron being recorded (200-500 mg/l), and the slopes of the removal curves indicate the potential for additional leaching of large quantities of some of the ions that contribute to hardness.

Calcium

Calcium concentrations and mass removals, shown in Figures 39 and 40, were similar to the results for hardness. Concentrations were recorded in the leachate from cell 2B, as was the case for many other parameters. Concentrations for the cells remained within 400-500 mg/l of each other after the initial peaks were achieved. Final concentrations at closure were approximately 8% of the peak values. Examination of the calcium concentrations from cell 1 during a time period when the leachate flow varied from

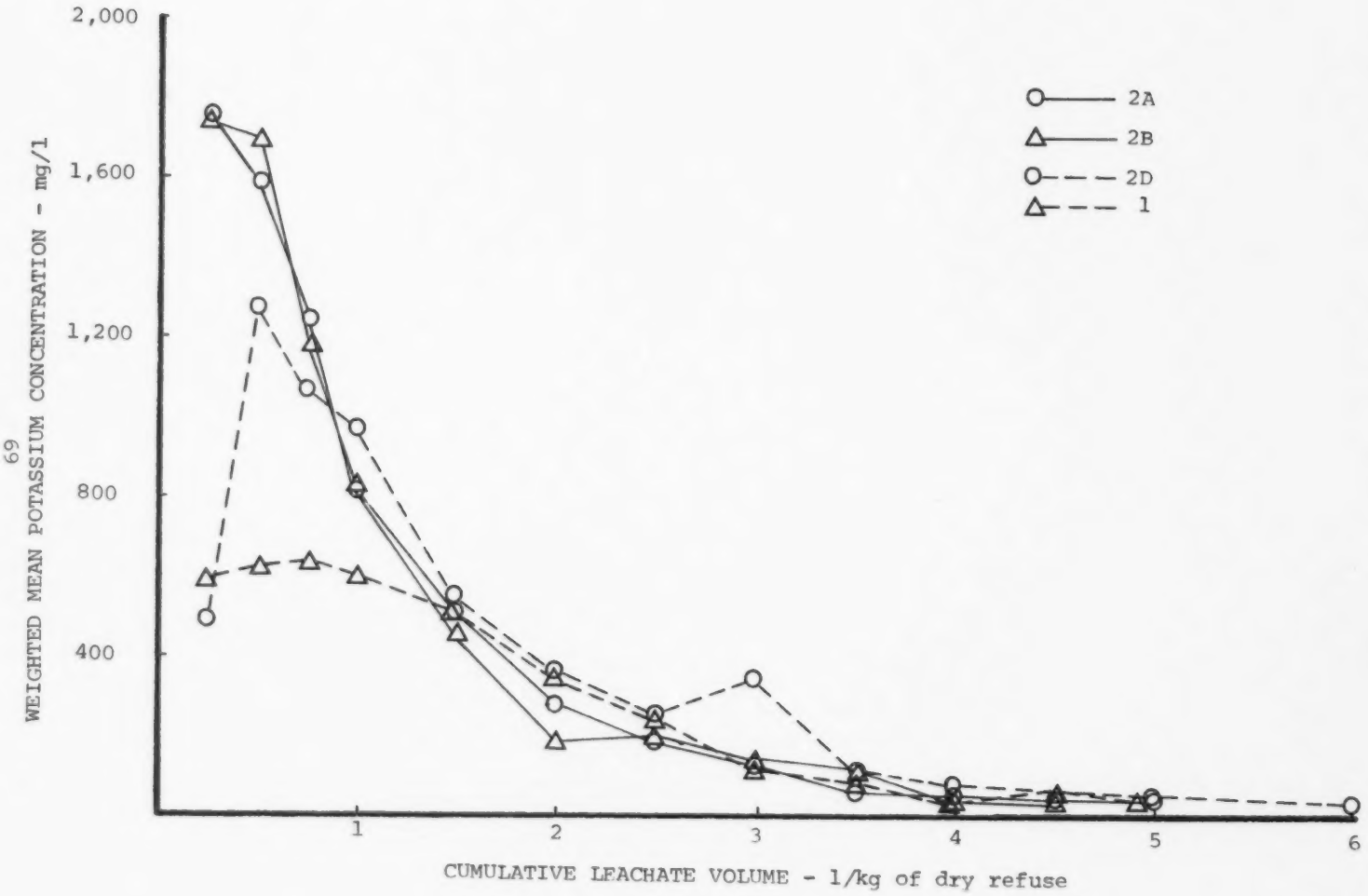


Figure 33. Potassium concentration history

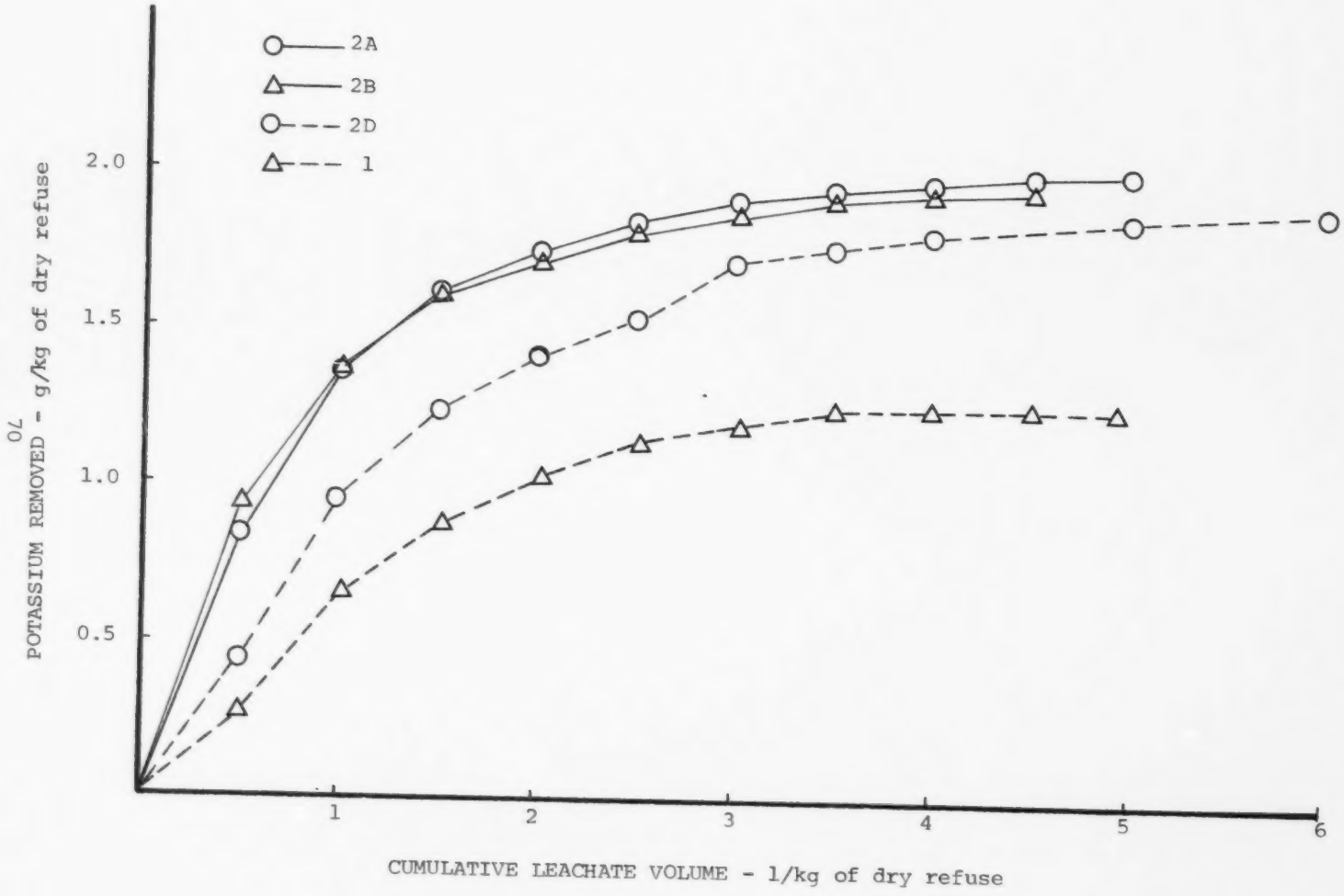


Figure 34. Potassium mass removal

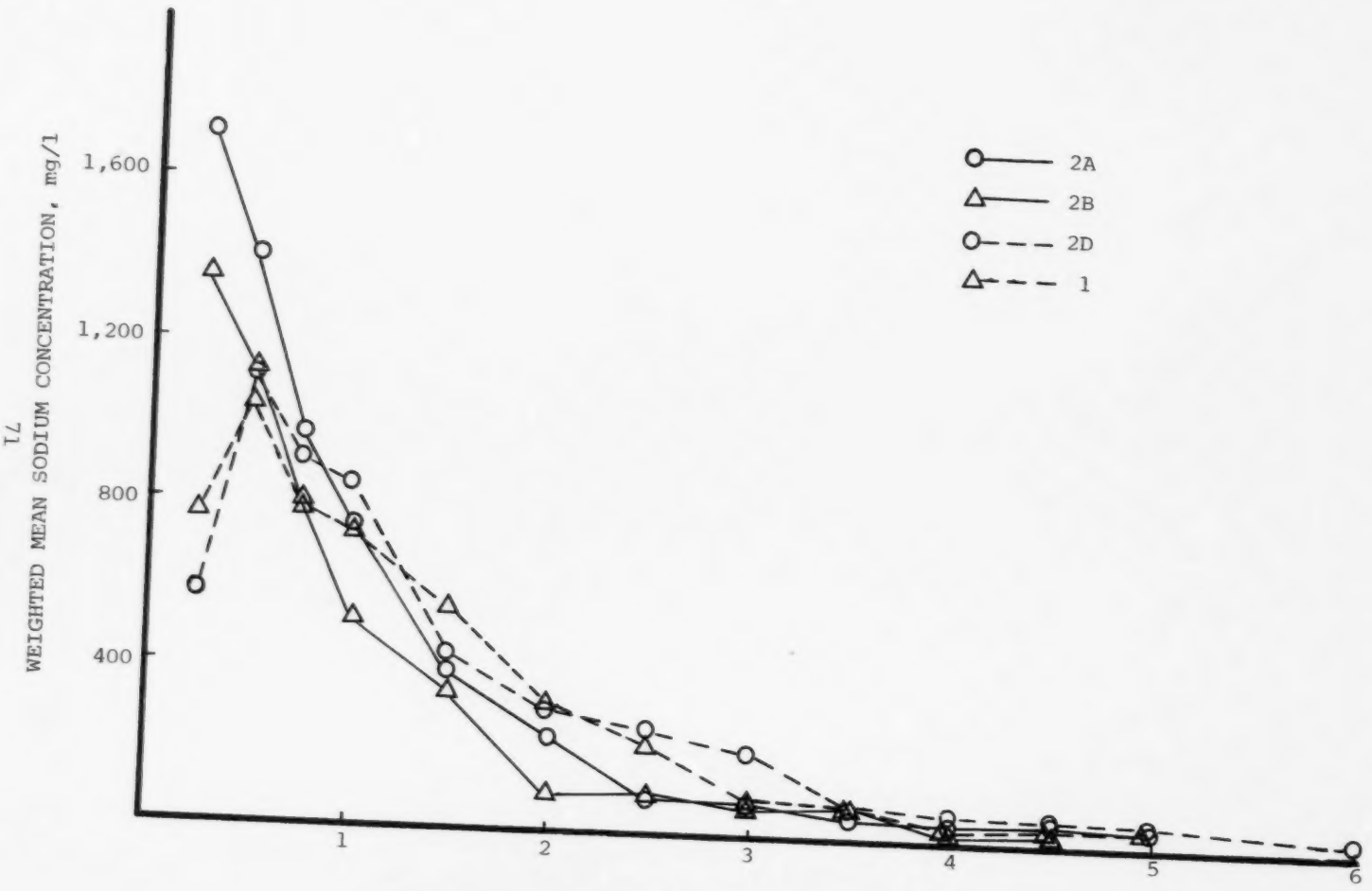


Figure 35. Sodium concentration history.

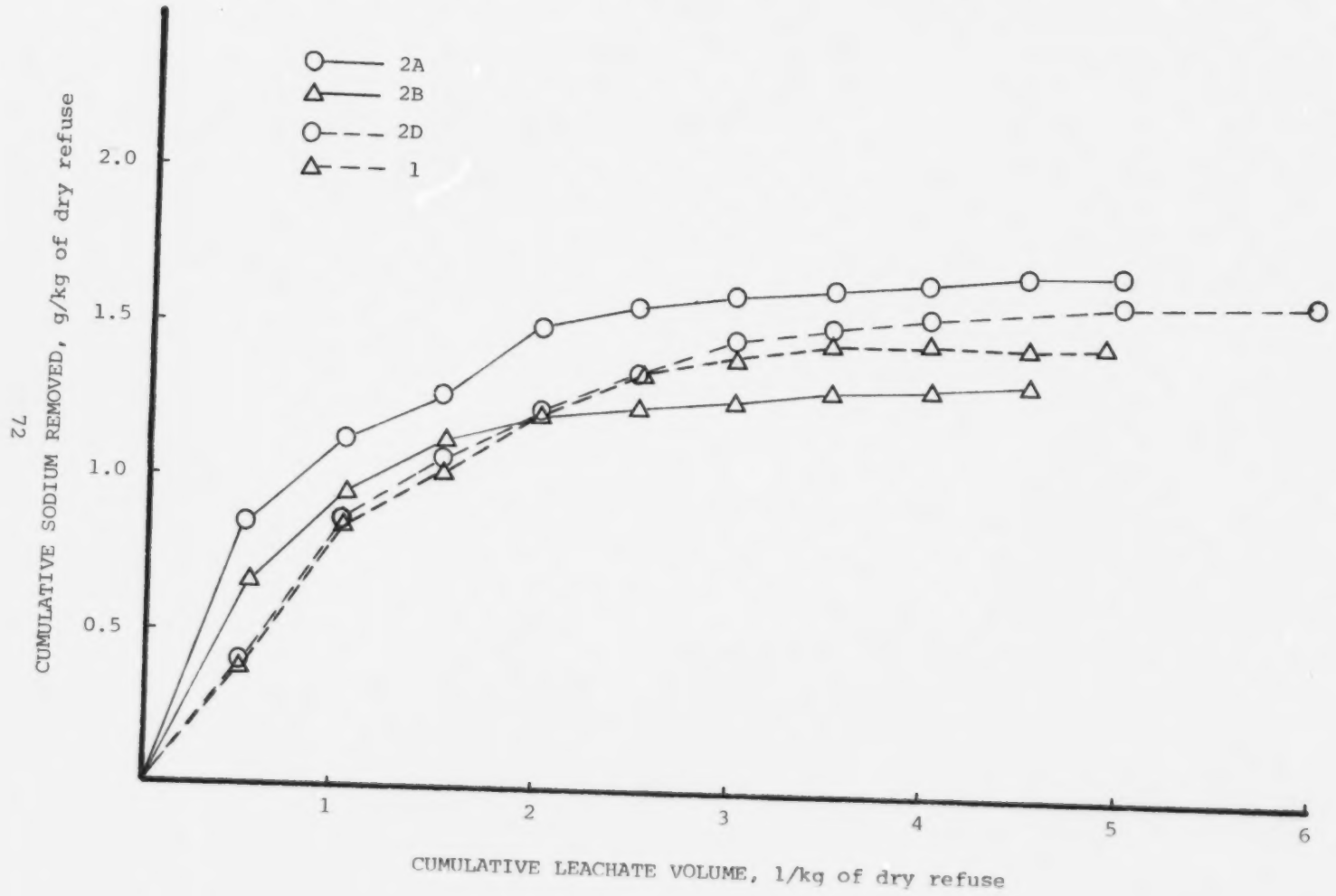


Figure 36. Sodium mass removal.

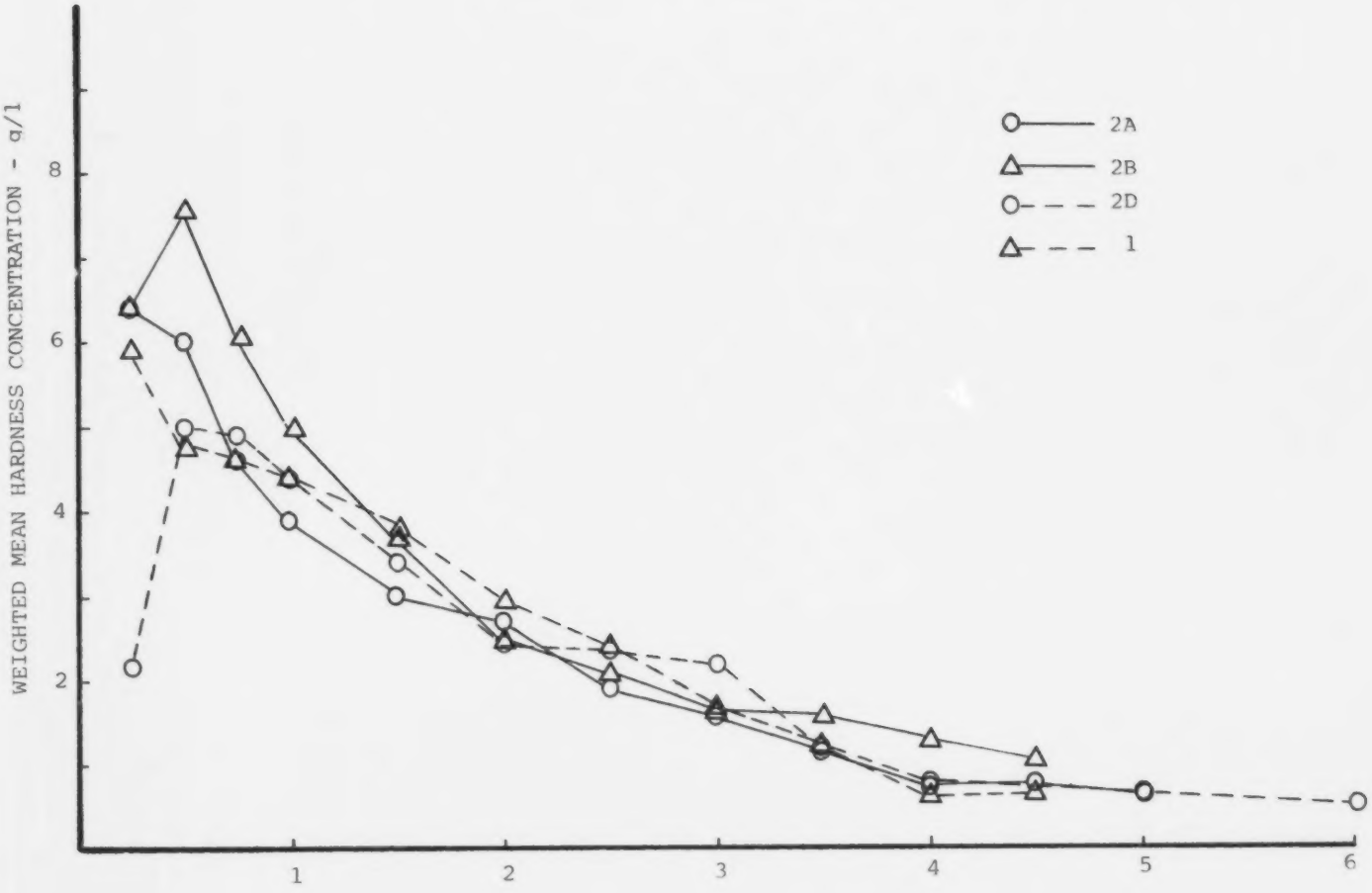


Figure 37. Hardness concentration history.

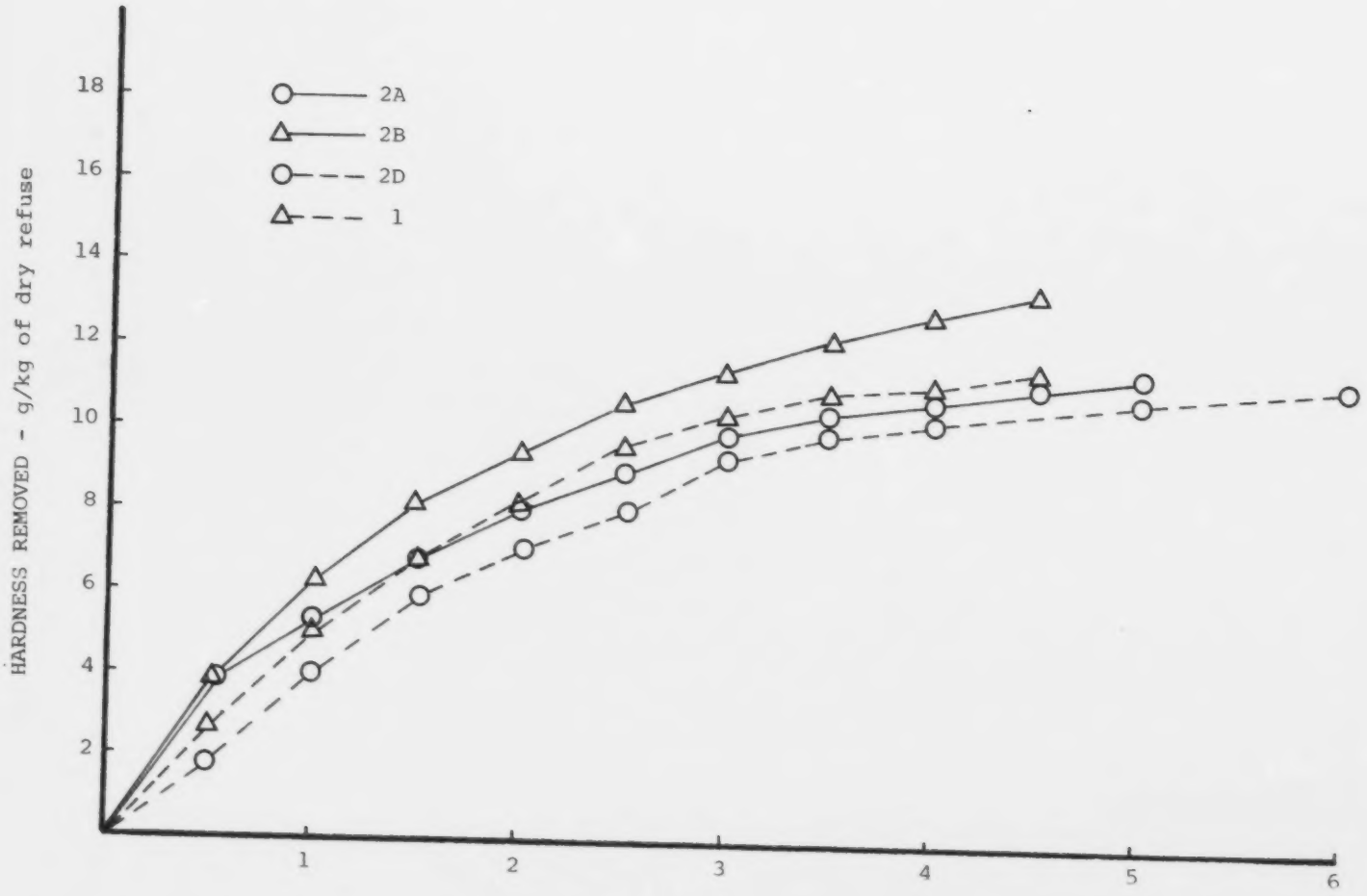


Figure 38. Hardness mass removal.

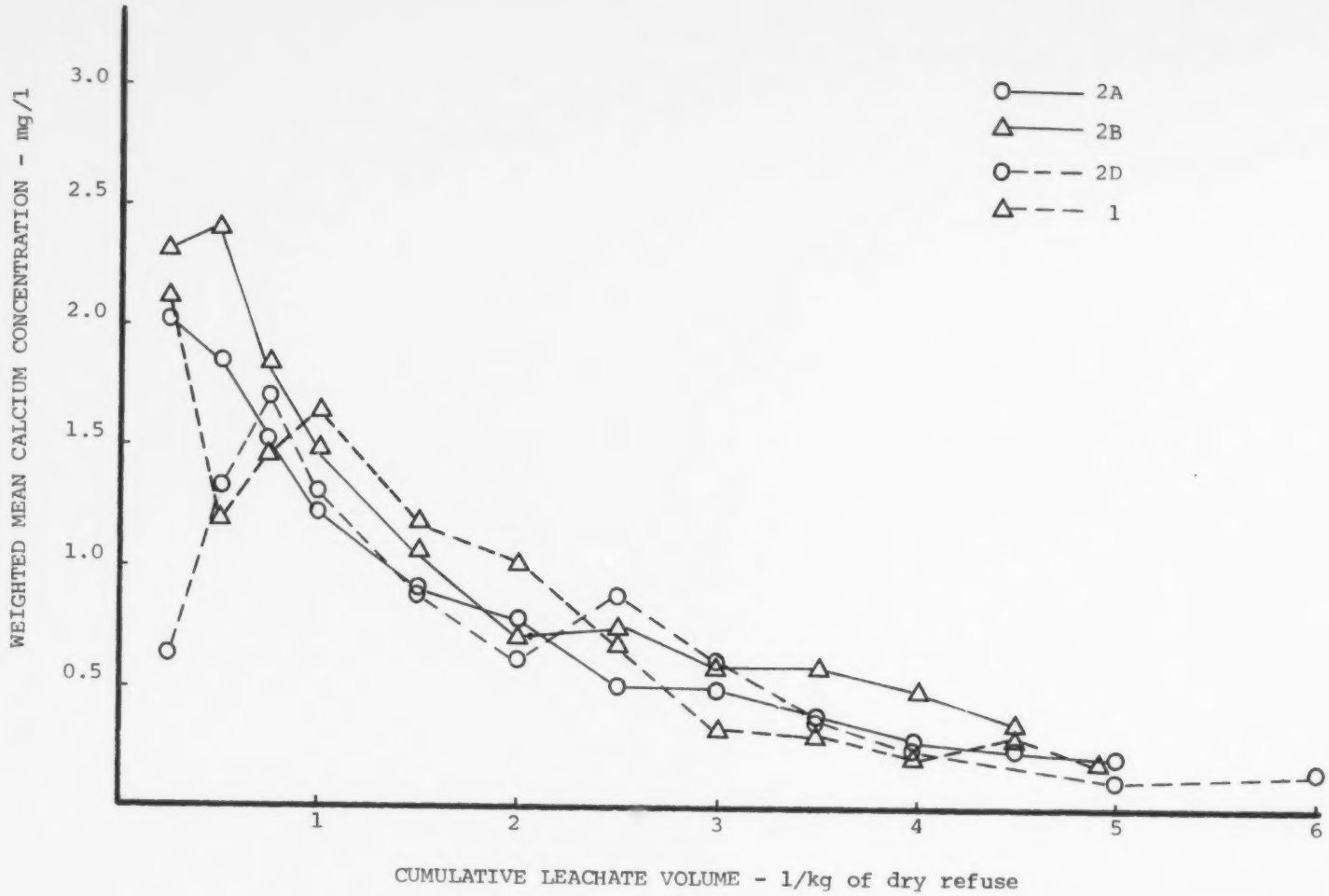


Figure 39. Calcium concentration history

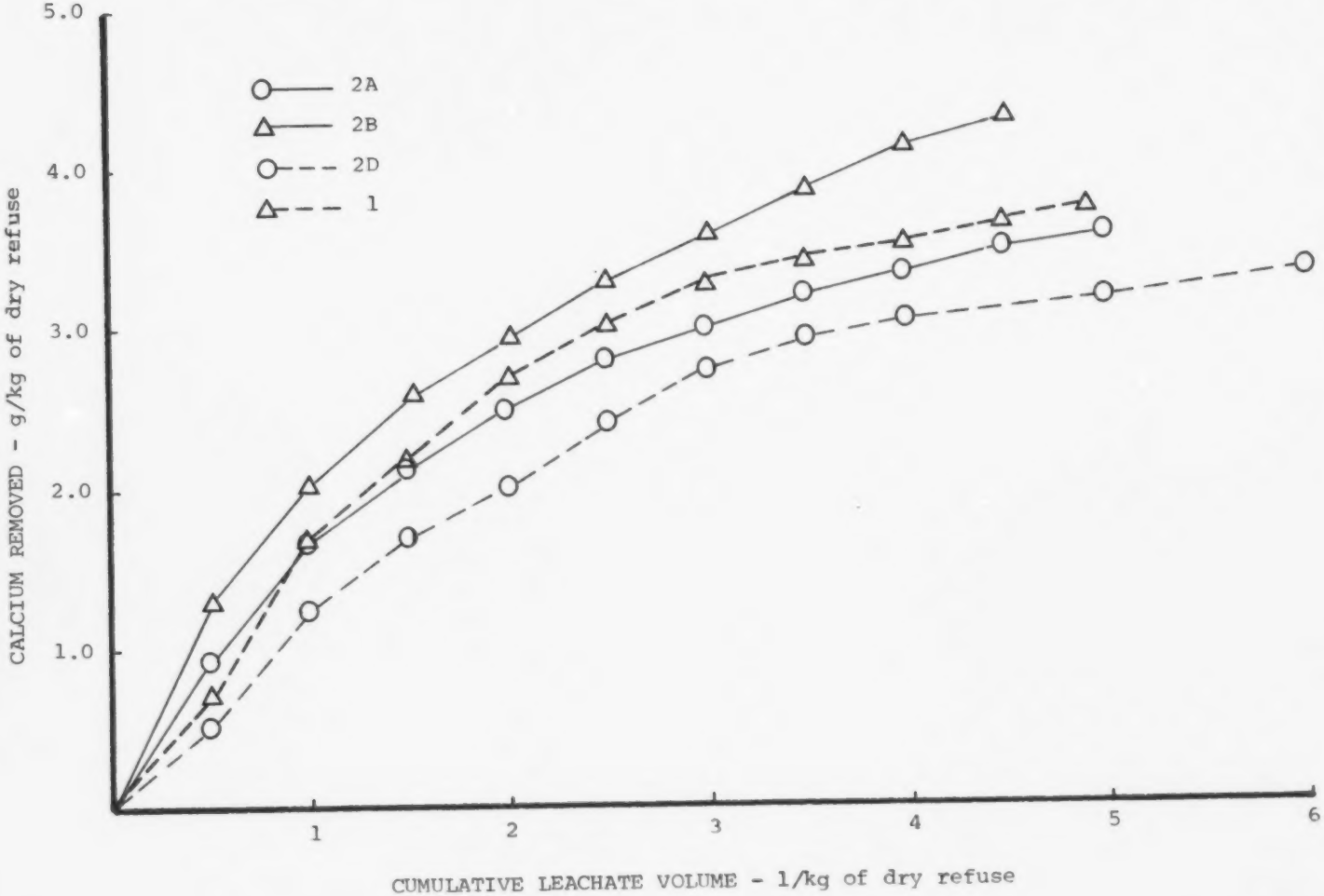


Figure 40. Calcium mass removal

5,400-57,000 liters/month indicated no correlation between concentration and flow volume. Cumulative mass of calcium removed from the cells varied from 3.1-4.3 g/kg of dry refuse, a wider range than for hardness. This difference was not only due to initial peak concentration variance but tended to increase with cumulative leachate. Approximately half the calcium was removed based on the initial value of 7.0 g/kg measured in the cell 1 refuse values.

Magnesium

Peak weighted mean concentrations of magnesium in the small cells, 2A and 2B, were almost 50% higher than those in the field scale cells as shown in Figure 41. The concentration in the small cells were similar in magnitude throughout the study while the results from cells 1 and 2D varied considerably until late in the study. Final concentrations were approximately 6% of the peak value.

Even with the wide variation in concentrations mass removals of magnesium from the four cells, as shown in Figure 42, were similar. Cumulative mass removed ranged from .52 g/kg in cell 1 to .62 g/kg in 2B. Most of this difference can be attributed to the early variations in concentrations. Initial magnesium was found to be 1.4 g/kg in cell 1 refuse. Magnesium in six residual samples removed from cell 1 at closure ranged from .47-1.12 g/kg of dry refuse.

Iron

The concentration and mass removal histories for total iron are plotted in Figures 43 and 44. Of the leachate parameter data studied, iron showed the greatest variation cell to cell and did not exhibit the same general peaking and downward trend with time. The erratic behavior appears to be in part due to pH changes, particularly the increase in concentrations recorded after 2.0 l/kg of leachate had been collected. This was the same point at which leachate pH (Figure 18) began to rise. A decrease in iron would have been expected. Concentrations of iron in water squeezed from refuse samples at closure ranged from 35-237 mg/l. These values and the gradual decline of concentrations shown in Figure 43 indicate a long-term iron removal pattern that would need to be considered in any treament design.

Mass removals of iron from cells 2A, 2B and 2D were very similar throughout the study. Removal from cell 1 at closure was only 60% of that from the other cells with a trend towards an increasing difference. Residual samples of refuse showed the iron remaining in cell 1 to be only 70% of that in the other cells, so the removal difference could possibly be related to the total amount of iron present in the cells.

Manganese

Manganese weighted mean concentrations and mass removals are shown in Figures 45-46. Concentrations in 2A and 2B leachate were almost identical throughout the study. The 2D peak was only 55% of the 2A-2B average.

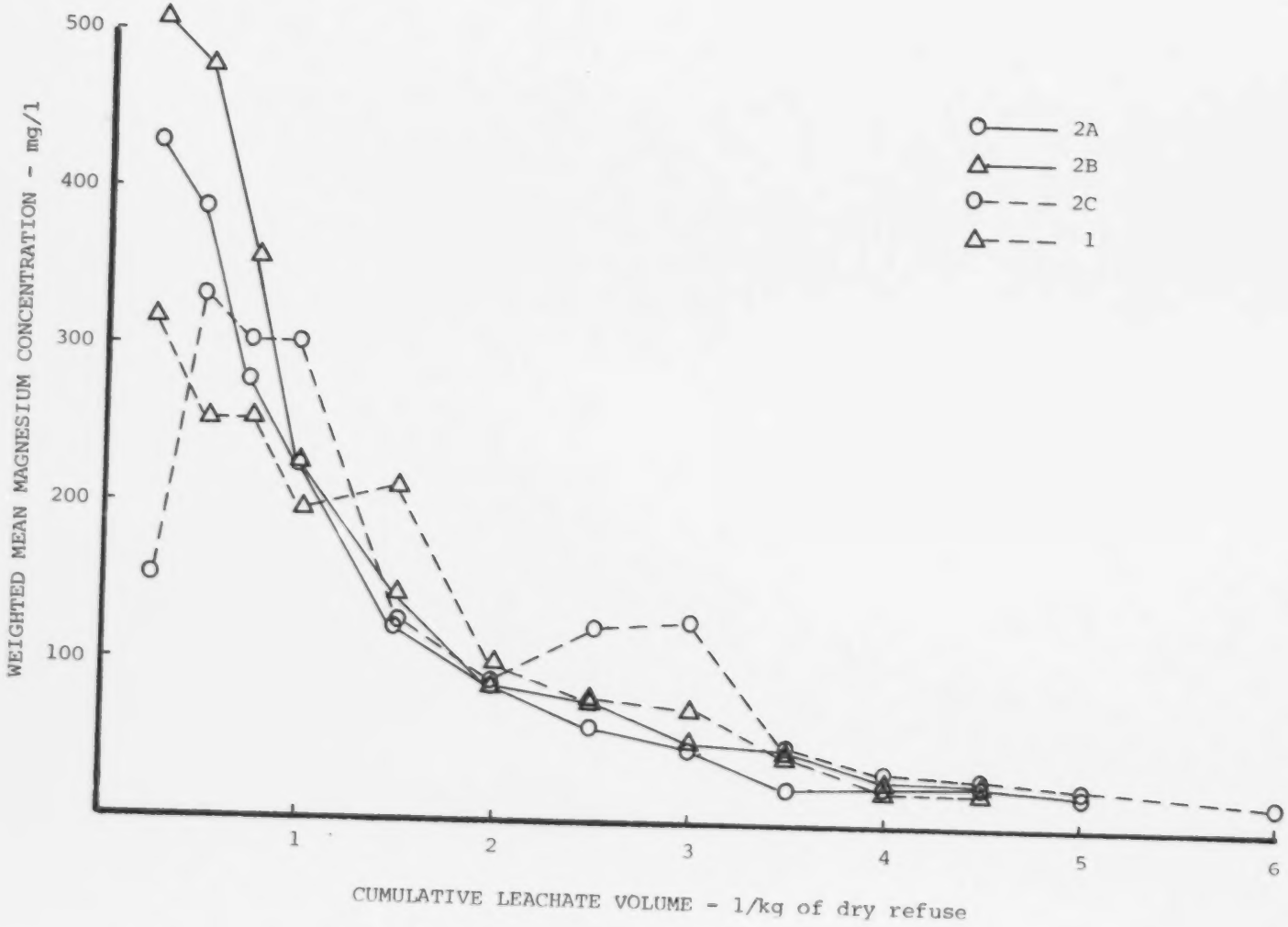


Figure 41. Magnesium concentration history.

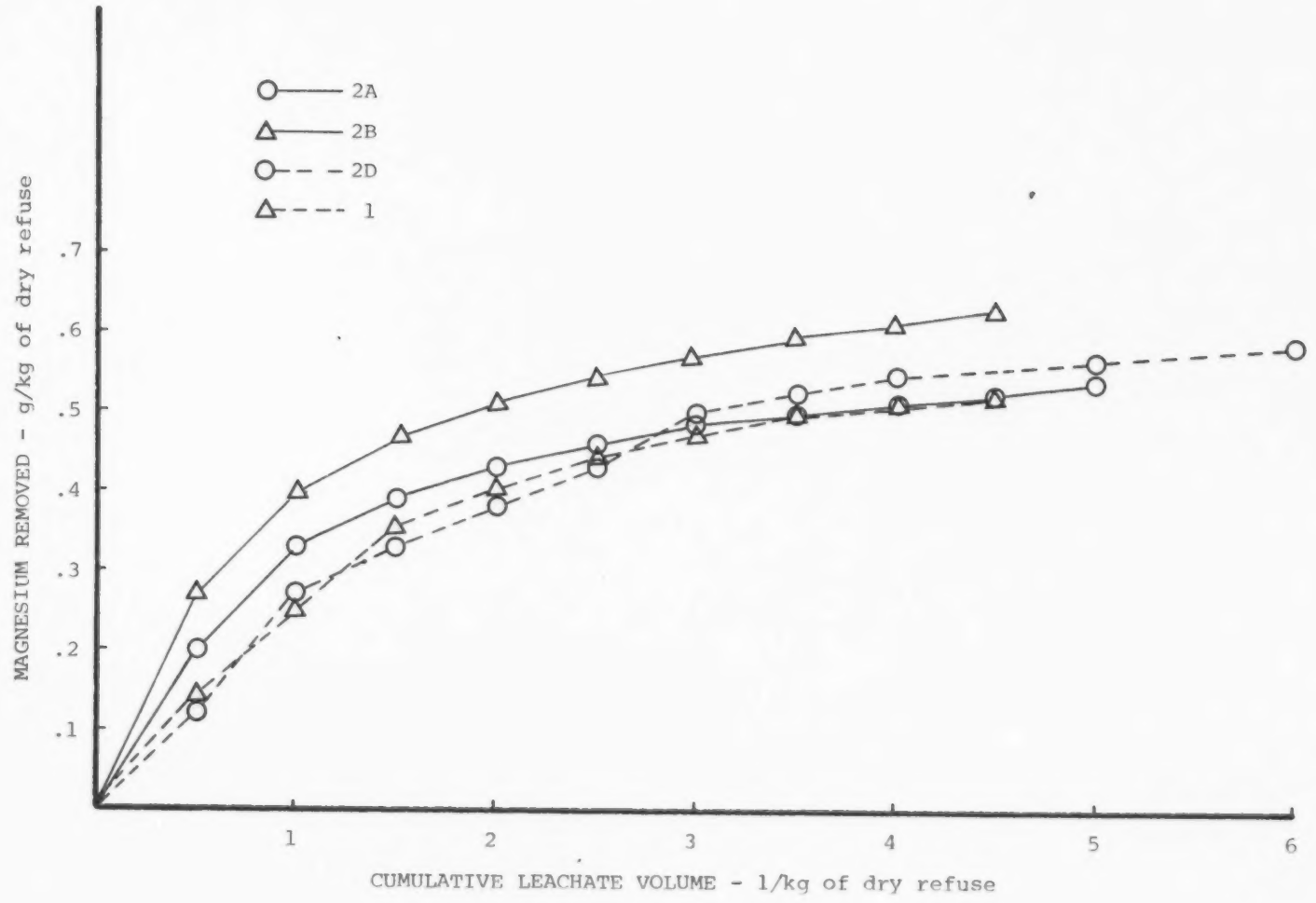


Figure 42. Magnesium mass removal.

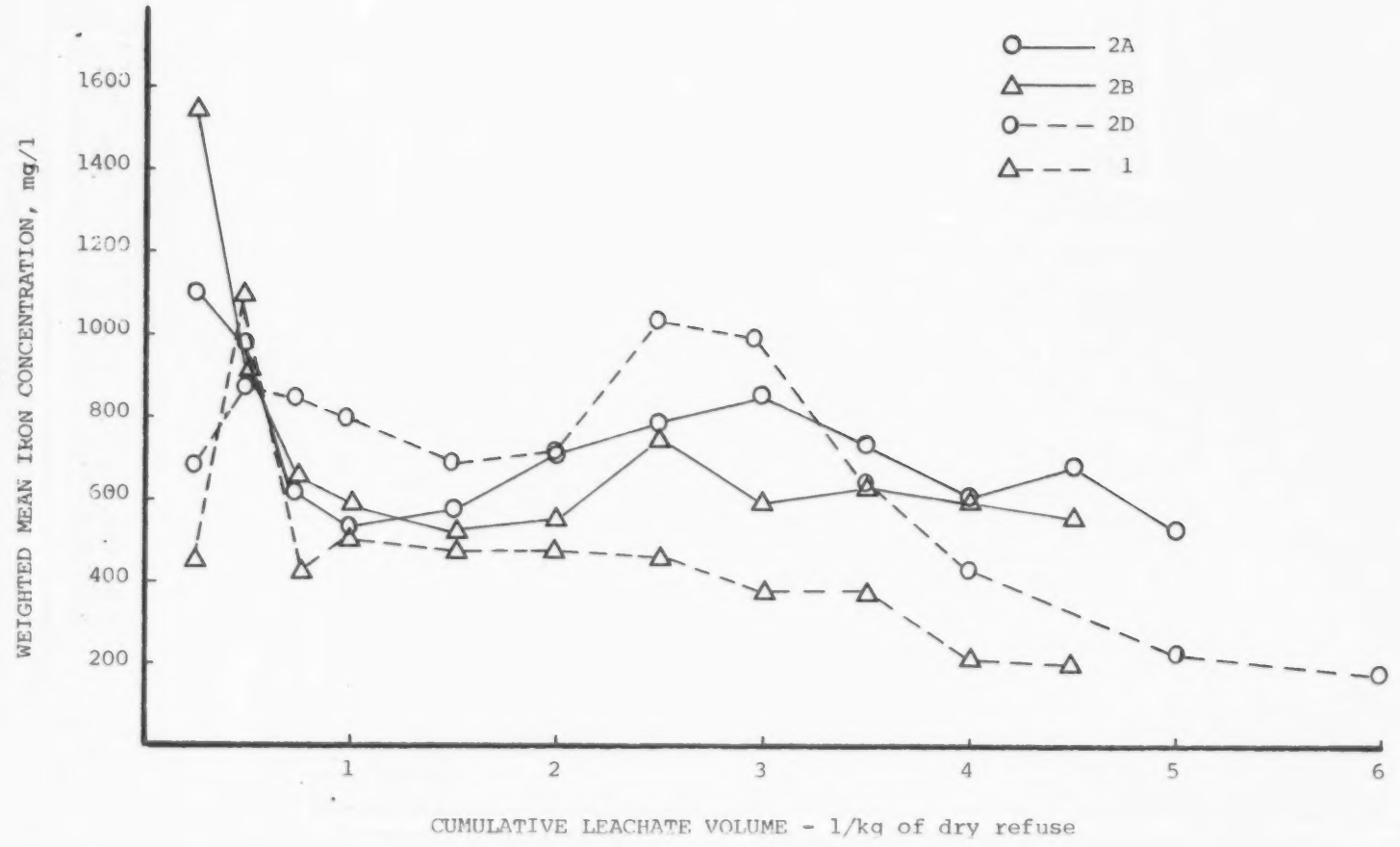


Figure 43. Iron concentration history.

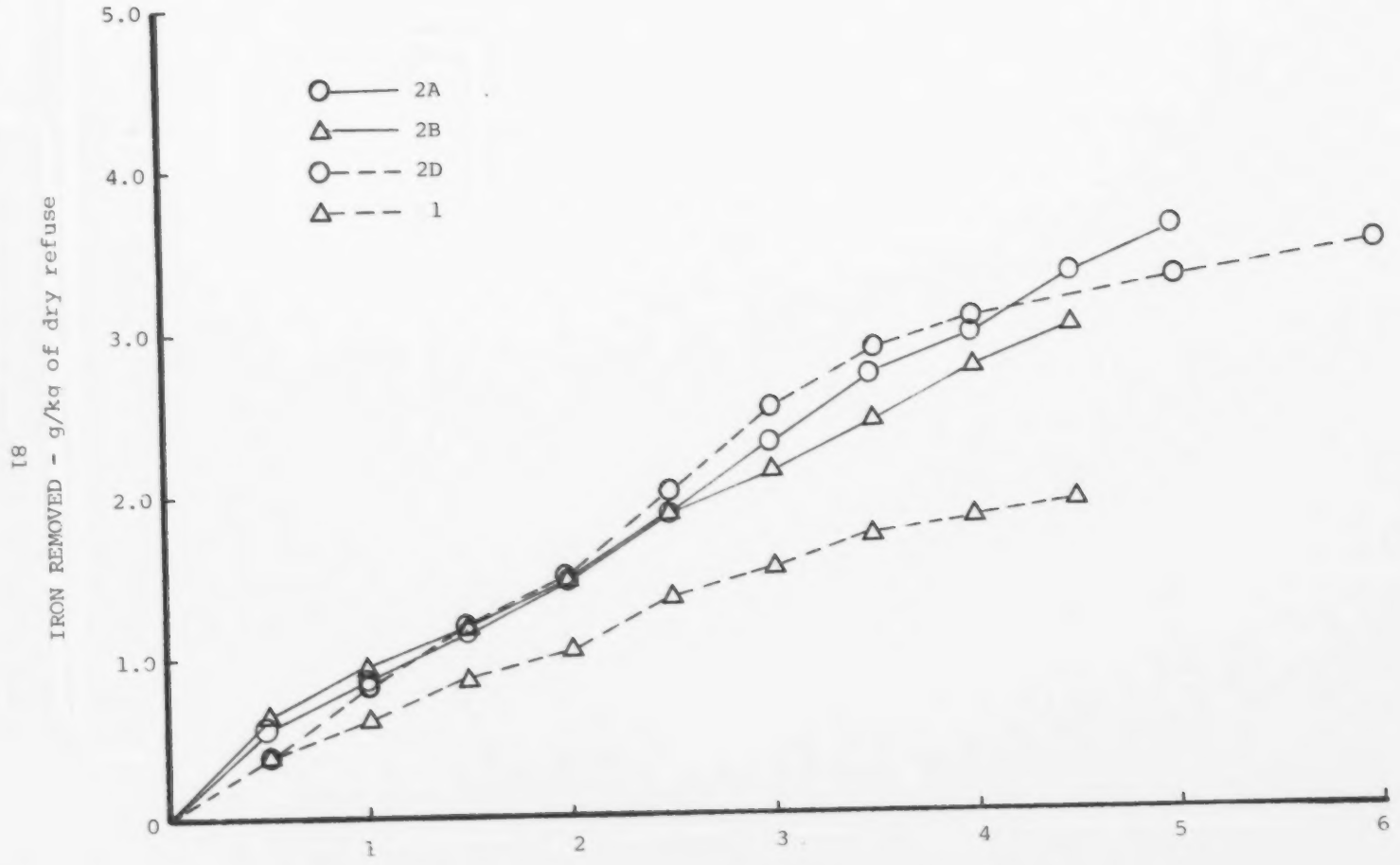


Figure 44. Iron mass removal.

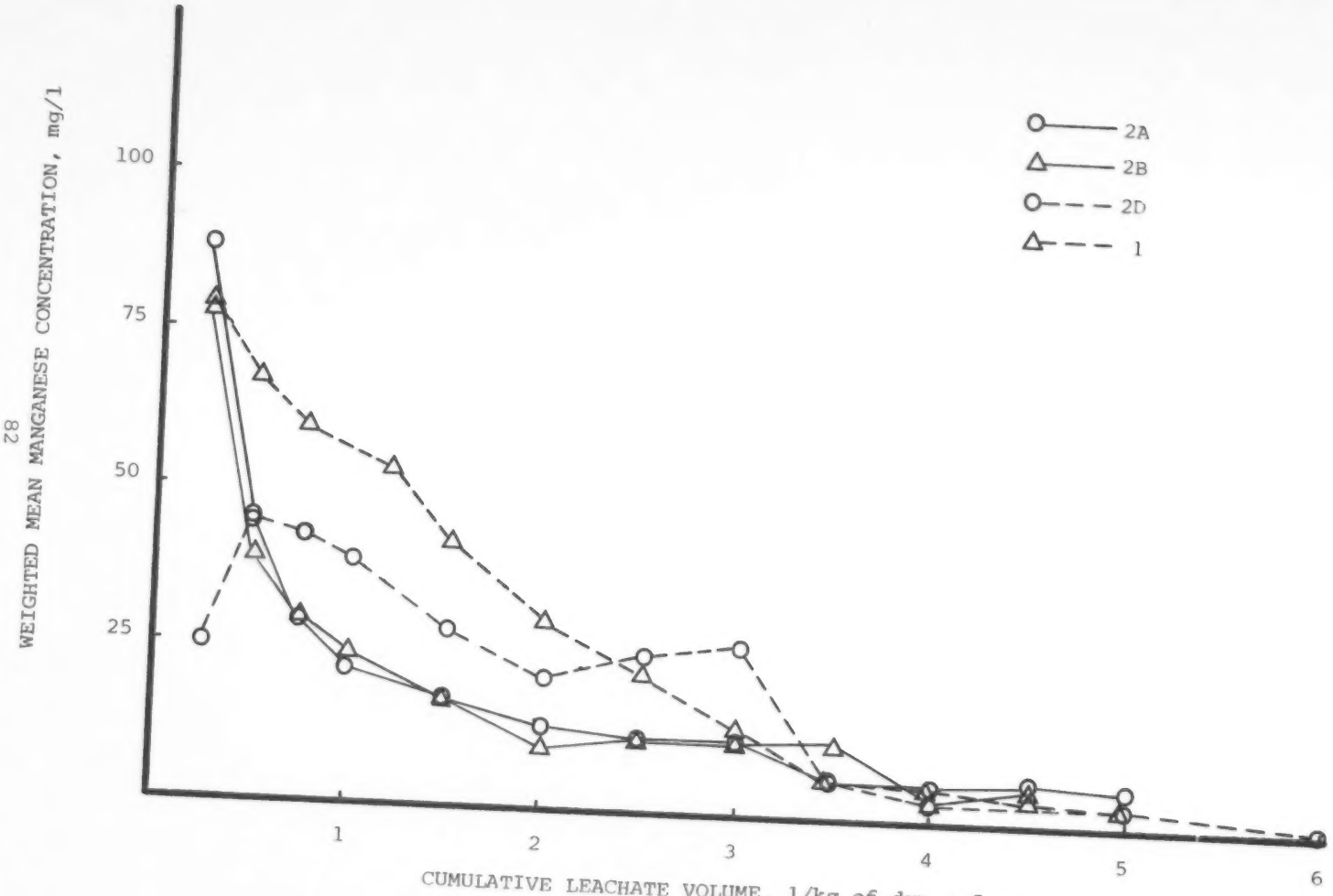


Figure 45. Manganese concentration history.

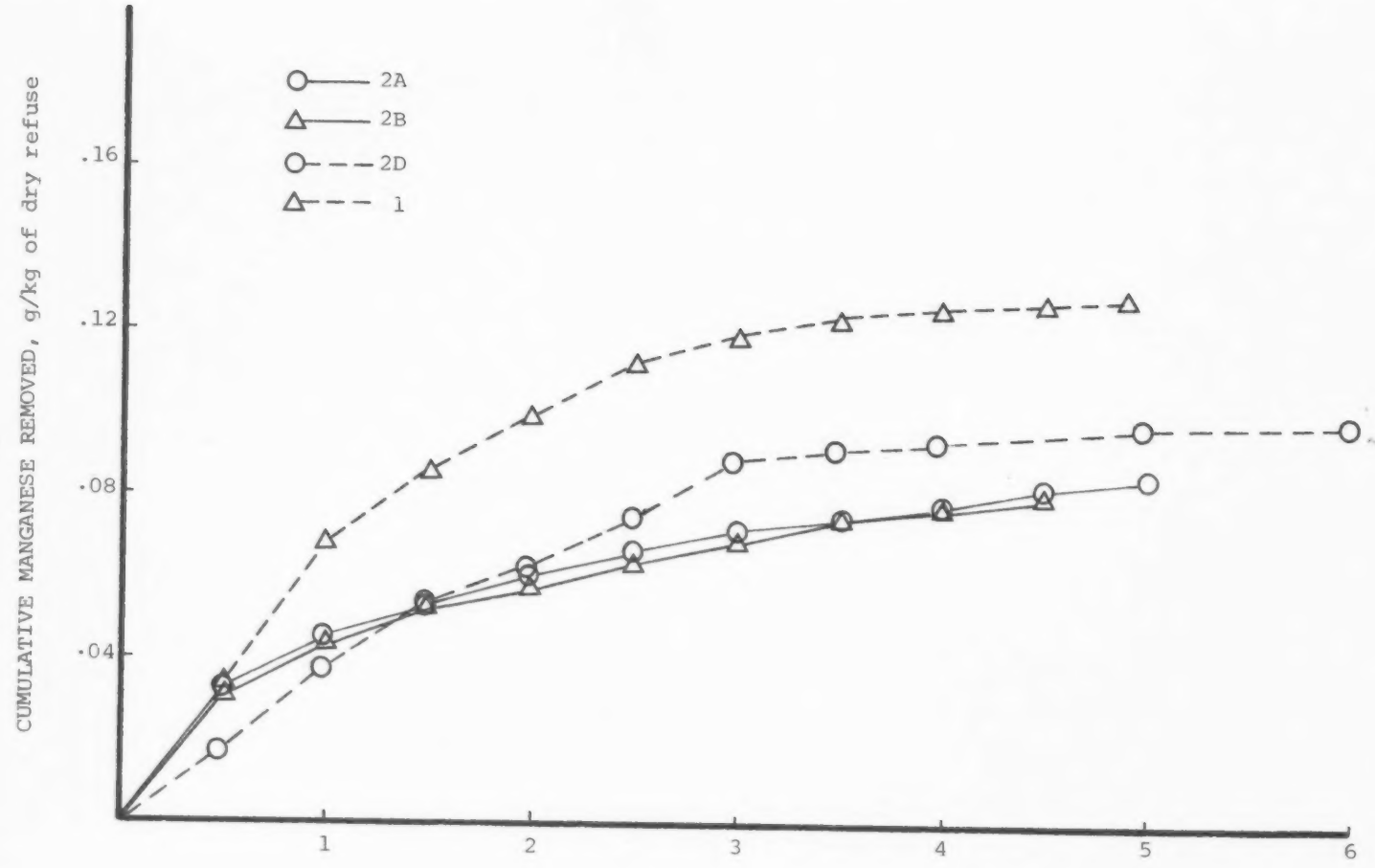


Figure 46. Manganese mass removal.

Concentrations at closure for all cells ranged from about 1-6 mg/l. As for iron, further long-term treatment of a leachate containing this quantity of manganese might be necessary since the recommended secondary drinking water standard is .05 mg/l.

Mass removal from the larger cells, 1 and 2D, was greater than that from 2A and 2B, contrary to the results for many of the other parameters. Removal totals and rates for 2A and 2B were almost identical. Total mass removals at closure ranged from .08-.13 g/kg of dry refuse. No initial or residual total refuse manganese analyses were performed.

Zinc

Figures 47 and 48 show the weighted mean concentrations and cumulative mass removal for zinc. A very high initial peak concentration in 2B leachate and continued high concentrations greater than the other cells indicate a high quantity of soluble zinc available in the 2B refuse. Concentrations and mass removals from the two large cells, 1 and 2D, were similar throughout the study. After 4.5 liters of leachate per dry kilogram of refuse had been collected the concentration of zinc had dropped below the recommended drinking water standard of 5 mg/l. Residual concentrations in the excess water squeezed from refuse samples at closure ranged from 5.7-19.8 mg/l.

Leachate Bioassays

During May, 1972, the 96 hour acute toxicities were determined for two leachate samples from cell 1 collected on May 8 and May 29. Fathead minnows, 5.1-6.3 cm in length, were acclimated to dechlorinated Cincinnati, Ohio tap water for one week prior to use.

Leachate test concentrations were prepared by mixing sample material with aerated diluent. The concentrations were then allowed to stand until ambient room temperature was reached (22^{o}C). Ten fish were placed in each test concentration and twenty fish in the control aquaria. Test aquaria were not aerated until the dissolved oxygen content fell below 3 mg/l. The test aquaria were then aerated continuously with compressed air to maintain 6 mg/l dissolved oxygen. No pH adjustment was made.

The 96 hour LC 50, or the percent of leachate required to kill 50 percent of the population during a 96 hour exposure was 2.5 and 2.1% for 2 series of tests run on the May 8 sample.

Microbiologic Studies

During the construction of cell 1, 36 PVC pipes were placed through the bulkhead of the observation unit to determine the effect of a landfill environment on inserted viral and bacterial pathogens and to evaluate the movement of the pathogens. A complete description of the testing procedure is contained in reference 11.

Baskets containing 3 bags of sterilized shredded refuse were inserted into the pipes. Two of the three bags were inoculated with either

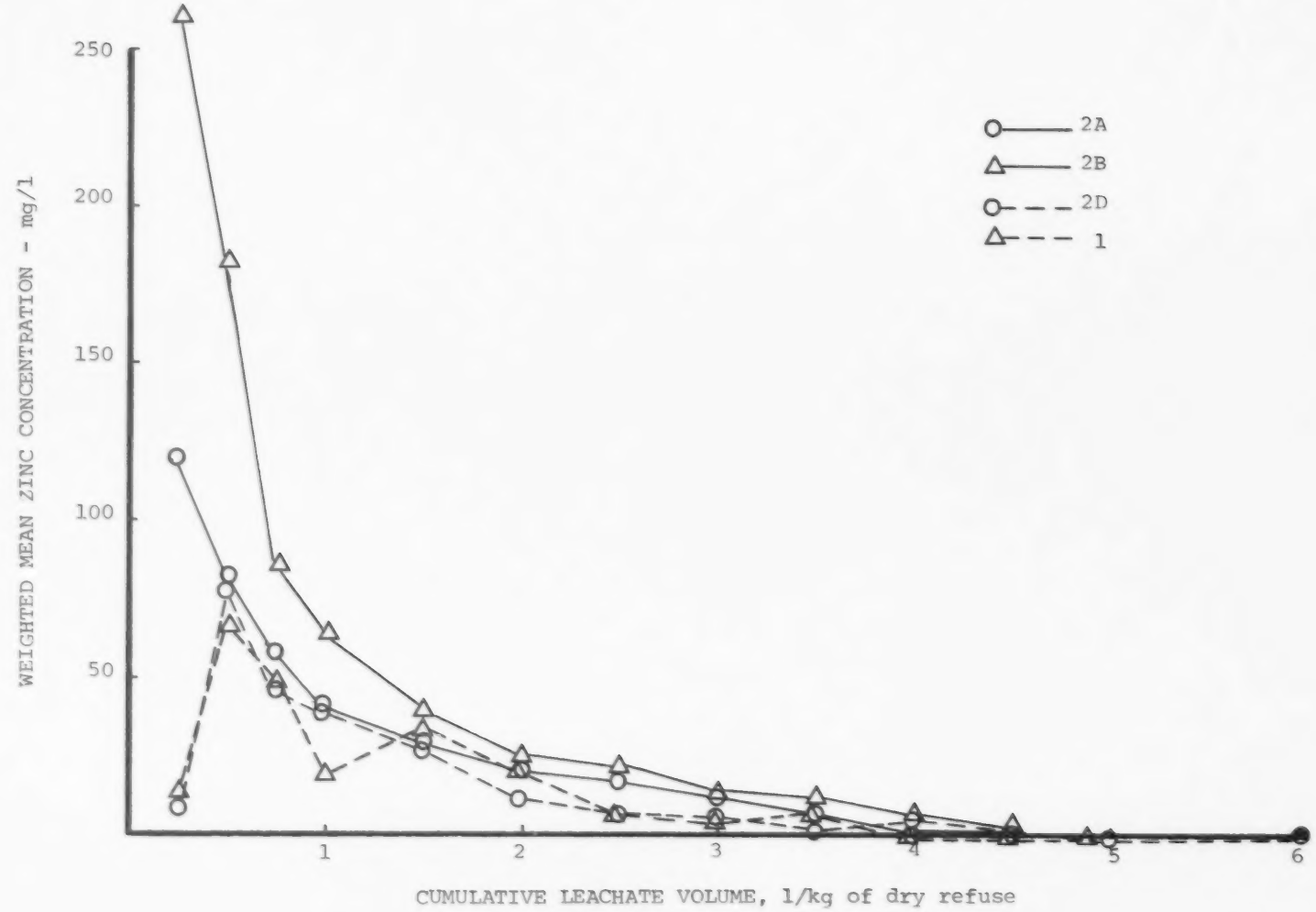


Figure 47. Zinc concentration history

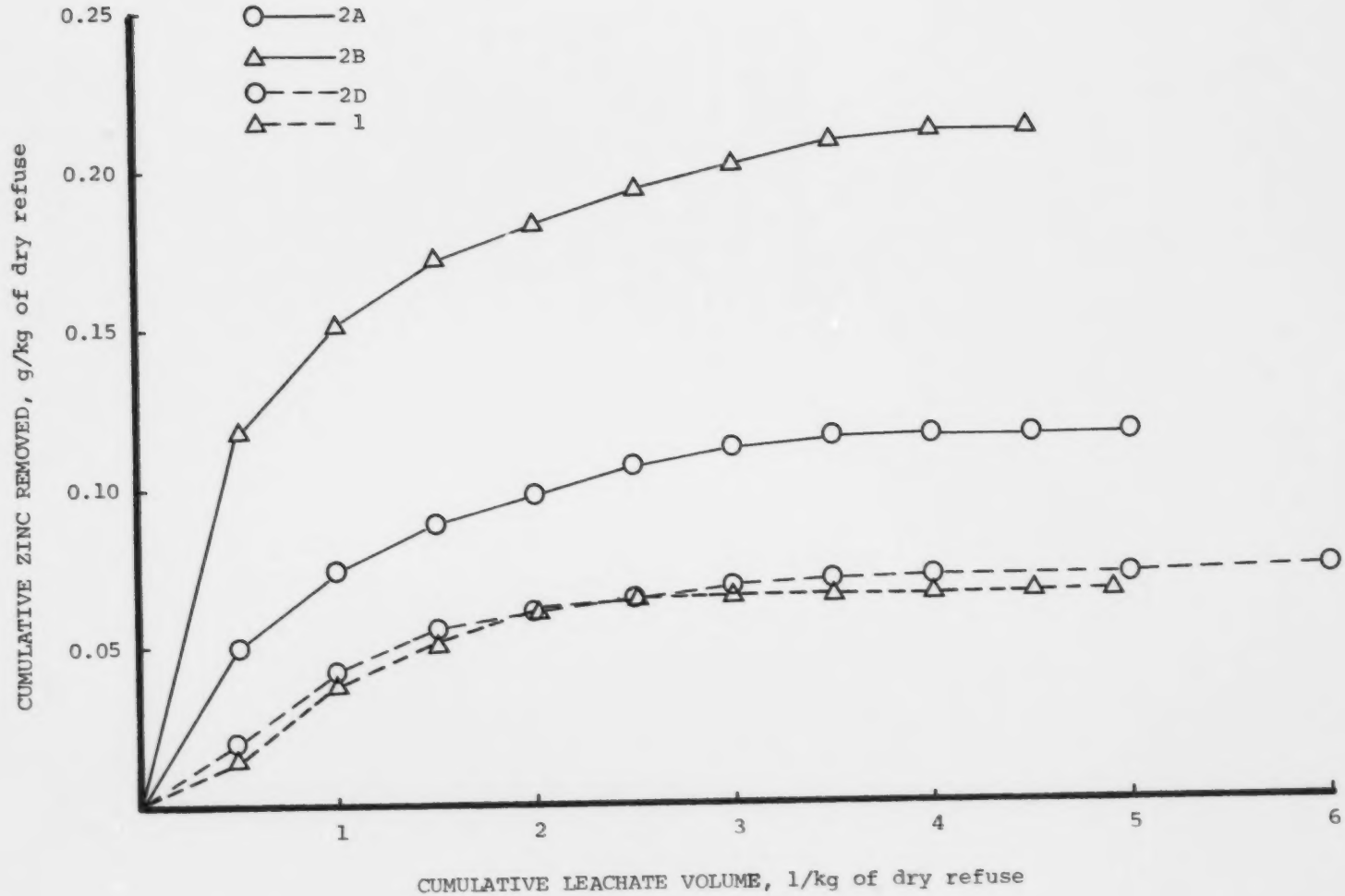


Figure 48. Zinc mass removal

polio-virus type 1 or Salmonella derby. The third bag, not seeded, was placed under the other two to monitor migration. Samples were taken at weekly and bi-weekly intervals extending over a three-month period. In summary, polio-virus type 1 and Salmonella derby were inactivated at the three test levels in less than 10 days exposure. Temperature appeared to be an essential factor in pathogen inactivation. Estimated peak temperatures were approximately 140°F.

Microbial densities in leachate collected from the cell 1 upper pipe during the first year are summarized in Table 18. Considerable variations in coliform densities existed from one sampling date to another. Organisms detected in leachates indicate that bacterial populations can be leached by the water moving through the refuse. The fecal coliform/fecal strep ratio during the first two month period ranged from .01-6.2, indicating the presence of fecal material from warm-blooded animals, including man, and possibly food waste discharges.

Additional microbiological sampling was conducted during closure of the landfill. The complete results are reported in reference 12. In summary, significant levels of fecal-indicators (i.e. total and fecal coliforms and fecal streptococci) were found in the landfill solid wastes at all depths, indicating that these microbes had continued to survive and reproduce for nine years. The low or non-existent microbial presence in the leachate samples from the cell over the past nine years did not therefore indicate the true microbial numbers residing in the wastes within the landfill. The high microbial numbers found in the water within the cell, and the high fecal-indicator levels present in the solid wastes, demonstrated that microbes can continue to dwell within the landfill for indefinite lengths of time, in this case nine years.

In addition, the identified pathogens found in the solid waste samples from cell 1 included Acinetobacter sp., Moraxella sp., Salmonella sp., and Klebsiella pneumoniae. Other nonpathogenic enterobacteriaceae and related Gram-negative rod bacteria were also found. These microorganisms were not found in the control soils.

Although the solid waste could have contained all kinds of human and animal fecal material, it was not found to be as heavily contaminated as sewage sludge. The results indicate that personnel associated with landfill operations, or those who later utilize landfilled sites, are at some risk as regards health impact.

Mathematical Description of Leachate Concentration History

The repetitive trends of leachate concentration for many of the parameters indicated that the weighted mean concentration history curves might be mathematically described. The need for such a descriptive model has been documented by Brunner [13]. A forecasting technique would provide a significant improvement in the design and regulatory review processes and could be used to determine optimal operational practices. Forecasting would be useful in evaluation and design of leachate treatment needs and the suitability of the hydrogeologic setting.

TABLE 18. MICROBIOLOGIC ANALYSIS OF LEACHATE - CELL 1 UPPER PIPE

Sampling Date	Bacterial Densities - Organisms per 100 ml (MPN) Total Coliforms	Fecal Coliforms	Fecal Streptococci
8-31-71	2.8×10^7	2.6×10^6	2.4×10^8
9-1	5.4×10^6	4.9×10^6	7.9×10^5
9-13	2×10^3	2×10^3	7.9×10^4
9-20	2.7×10^4	9×10^3	3.3×10^4
9-27	3.3×10^4	3.3×10^4	1.70×10^5
10-4	$<2 \times 10^2$	$<2 \times 10^2$	$<2 \times 10^2$
10-11	$<2 \times 10^2$	$<2 \times 10^2$	$<2 \times 10^2$
10-18	$<2 \times 10^2$	$<2 \times 10^2$	2.3×10^3
10-25	$<2 \times 10^2$	$<2 \times 10^2$	3.3×10^3
12-6	3.5×10^4	2.4×10^4	7.9×10^4
12-13	8×10^2	5×10^2	7.9×10^5
1-31-72	$<2 \times 10^2$	$<2 \times 10^2$	1.3×10^3
2-10	$<2 \times 10^3$	$<2 \times 10^2$	1.3×10^4
2-17	2.3×10^3	5×10^2	1.4×10^4
2-28	3.3×10^3	2×10^2	2.2×10^4
3-9	9.4×10^2	8×10^2	5.4×10^2
3-23	$<2 \times 10^1$	$<2 \times 10^1$	5×10^1
4-4	$<2 \times 10^1$	$<2 \times 10^1$	5×10^4
4-10	2×10^4	$<2 \times 10^1$	5.4×10^5
4-17	2.2×10^3	$<2 \times 10^1$	1.6×10^4
4-24	2.4×10^1	$<2 \times 10^1$	5.4×10^2
5-1	$<2 \times 10^1$	$<2 \times 10^1$	3.4×10^3
5-8	$<2 \times 10^3$	$<2 \times 10^2$	2.2×10^4
5-15	1.7×10^1	1.1×10^1	2.4×10^3
5-22	$<2 \times 10^1$	$<2 \times 10^1$	1.7×10^1
5-29	$<2 \times 10^1$	$<2 \times 10^1$	$<2 \times 10^2$
6-5	$<2 \times 10^1$	$<2 \times 10^1$	1.3×10^2
6-12	$<2 \times 10^1$	$<2 \times 10^1$	7.9×10^4
6-20	$<2 \times 10^1$	$<2 \times 10^1$	9.2×10^2
6-26	$<2 \times 10^1$	$<2 \times 10^1$	7.9×10^2

The leachate concentrations are dependent on many factors, not all of which are understood or known, especially the magnitude of influence the factors exert on resultant concentrations. Important variables might be the initial mass of a substance readily available for leaching, decomposition of refuse within the fill and subsequent additional mass availability, the pH, solubility limits, the rate of water throughout, decomposition or reduction of the leachate constituents during travel through the fill, the depth of the fill and cover soil effects within the fill. The number of variables involved and the lack of understanding of their effect on resultant leachate concentrations make a simple semi-empirical approach attractive. Previous efforts have been reported by Phelps[14], Straub[15], and in the interim report on cells 2A-2D [4].

One option in modeling leachate concentration is to consider the refuse mass as a single well-mixed reactor[15]. Such a system is depicted in Figure 49.

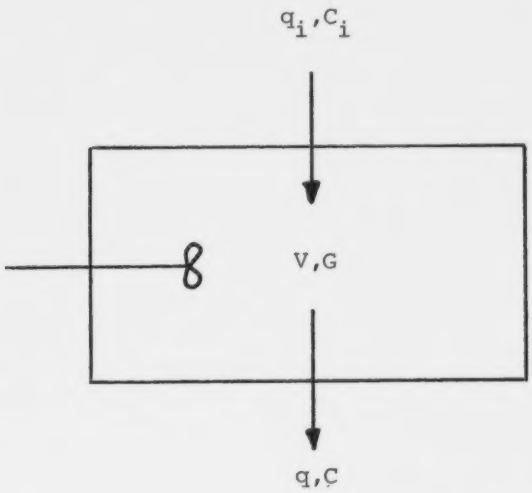


Figure 49. Well-mixed reactor

C_i and C are the input water and leachate concentrations. q_i and q are input water and leachate flow rates respectively. V is the total water contained in the refuse system (field capacity) and G is the internal mass generation rate.

Writing a mass balance on the reactor yields:

$$\frac{dVC}{dt} = q_i C_i - qC + G \qquad (1)$$

or the time rate of change of mass within the system equals mass inflow less outflow plus internal generation. This can be further simplified by assuming that the incoming concentrations are negligible, and that the volume of water within the system is constant or $q_i = q$ and V is a constant. This yields:

$$\frac{VdC}{dt} = - qC + G \qquad (2)$$

To solve the differential equation, an expression for G is necessary. One option is to consider the mass generation as a first order reaction as is commonly done for biochemical decomposition. This expression is simply $G = kVC$, or the rate of mass generation is proportional to the amount of mass present, with k being the rate coefficient. The differential equation becomes:

$$\frac{VdC}{dt} = - qC + kVC \qquad (3)$$

which when solved for $C = C_o$ at $t = o$ yields:

$$C = C_o e^{-(q/V - k)t} \quad (4)$$

Thus, a general expression for the concentration change with time with t = o at field capacity is a simple exponential dependent on the initial concentration C_o, the leachate flow rate q, total volume of water in the refuse at field capacity V, and an empirical rate constant k.

For most of the parameters studied, peak concentrations were recorded when field capacity was being achieved. C_o was therefore selected as that peak concentration for each parameter. V can be calculated for each test cell from initial moisture contents and field capacity determinations. The leachate flow rate q must be constant with time to be valid in the equation. This value was determined by least squares analysis of leachate collected with time. The resultant constants for each test cell are listed in Table 19.

TABLE 19. TEST CELL CONSTANTS

Cell	q[a]	v[b]	q/v
1	.57	1.22	.47
2A	.60	1.13	.53
2B	.58	1.13	.52
2D	.82	1.38	.59

a. liters/kg of dry refuse/year

b. liters/kg of dry refuse

Comparisons of the general equation with the weighted mean concentrations from 2A for five parameters are shown in Figures 50-54. Equation constants were determined by least squares. Reasonably good fit ($r>.90$) to the data is evident except for iron. Similar results were obtained for the other test cells. The equation constants and the least squares correlation coefficients for all four cells are listed in Table 20.

It is interesting to note from Table 20 that the mass transfer coefficient (k) for chloride was approximately zero for the four cells, indicating that all the leachable mass present in the refuse was readily available and independent of biochemical reactions within the test cells. Iron had the highest k value or greatest rate of mass being transferred from the refuse to the water within the cell. Coefficients for the large scale cells, 1 and 2D, were generally lower than for 2A and 2B perhaps due to the diluting leakage or lower initial concentrations due to greater short-circuiting.

As seen in Figures 50-54 the value of Equation 4 was lower than the weighted mean data for the initial 2-3 data points. The first point on the weighted mean plot represents data recorded during leachate collection from the onset of leaching to .25 l/kg of leachate, a flow period during which

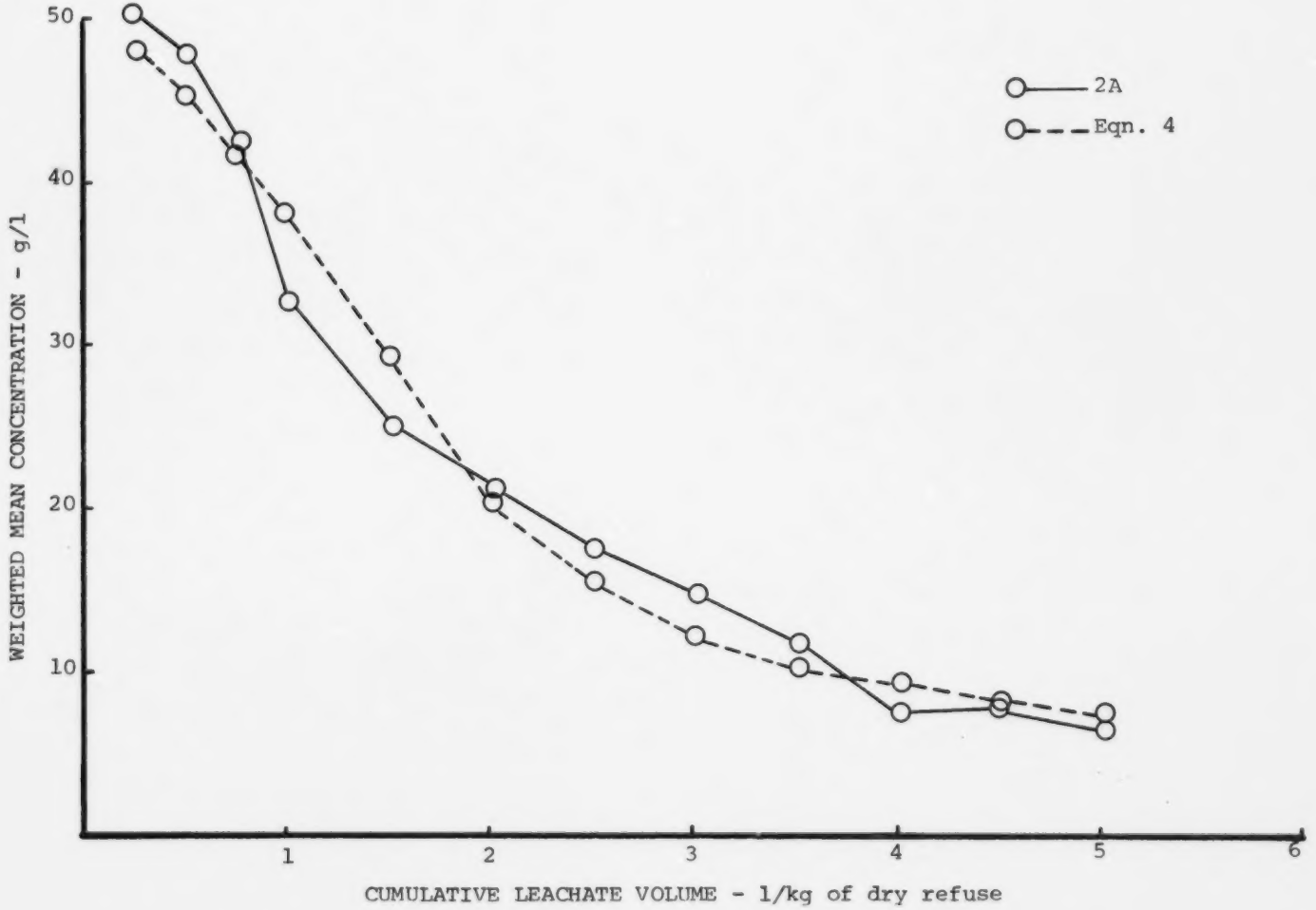


Figure 50. Cell 2A - COD concentration comparison

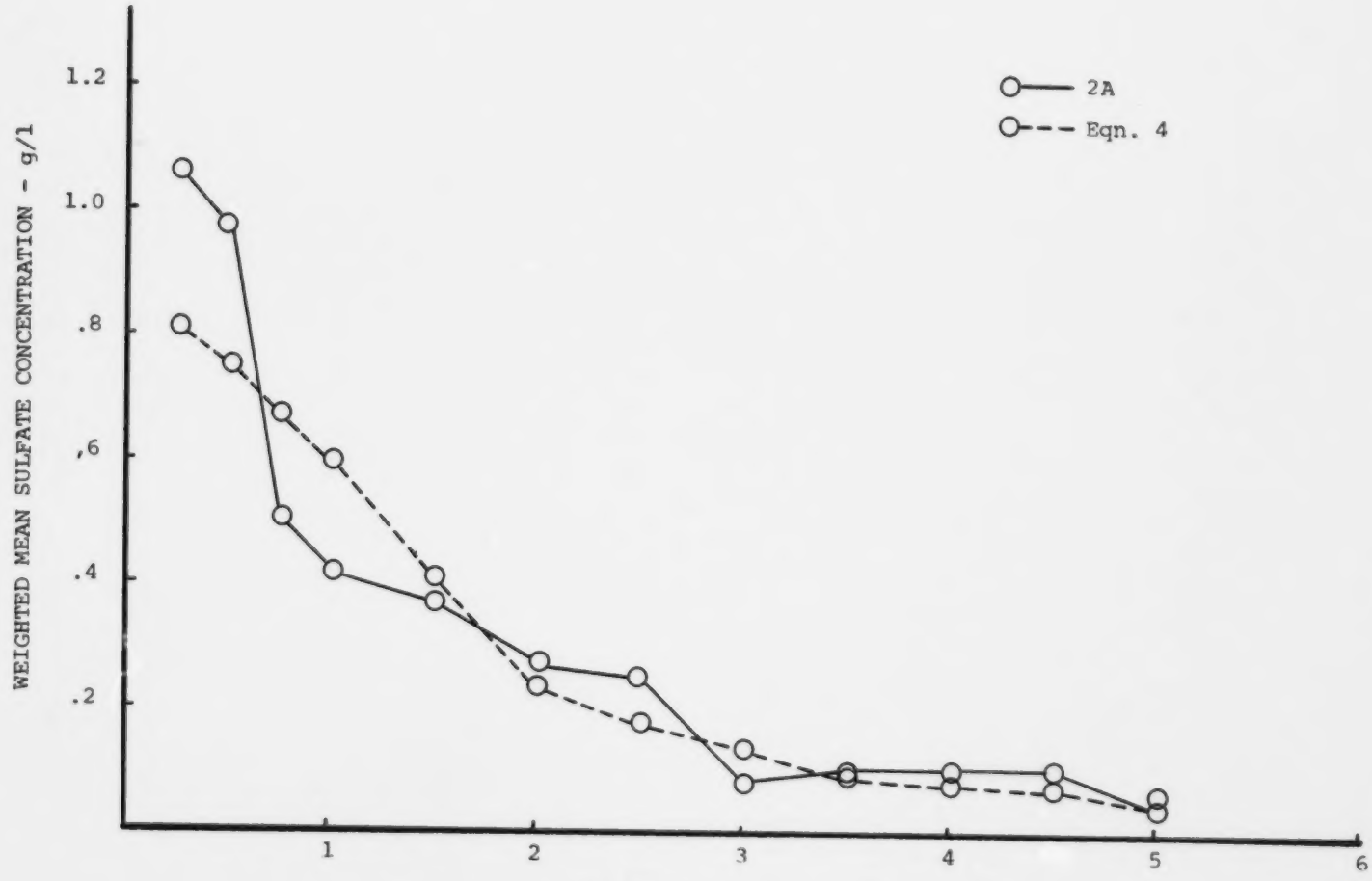


Figure 51. Cell 2A - Sulfate concentration comparison

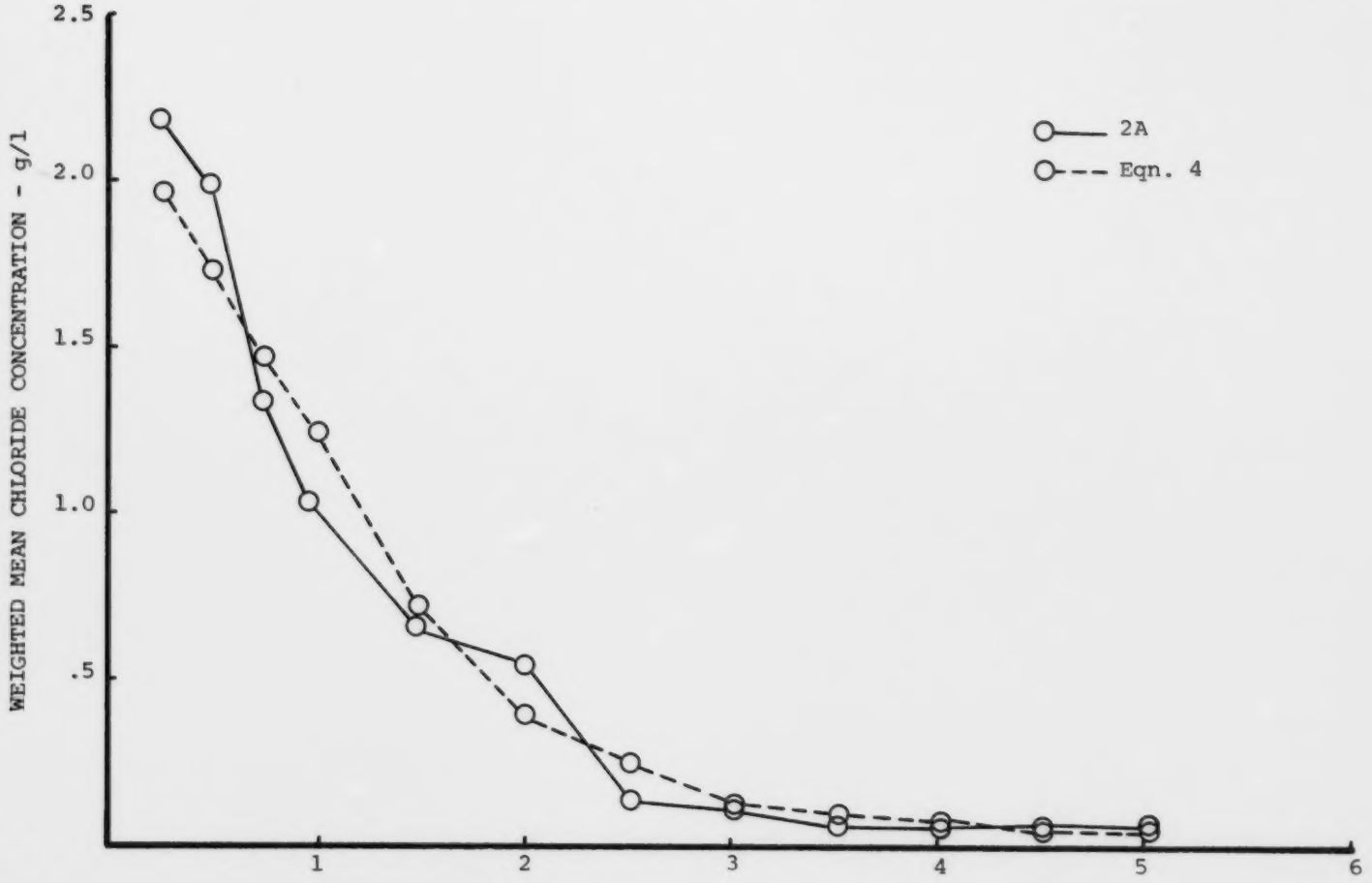


Figure 52. Chloride concentration comparison

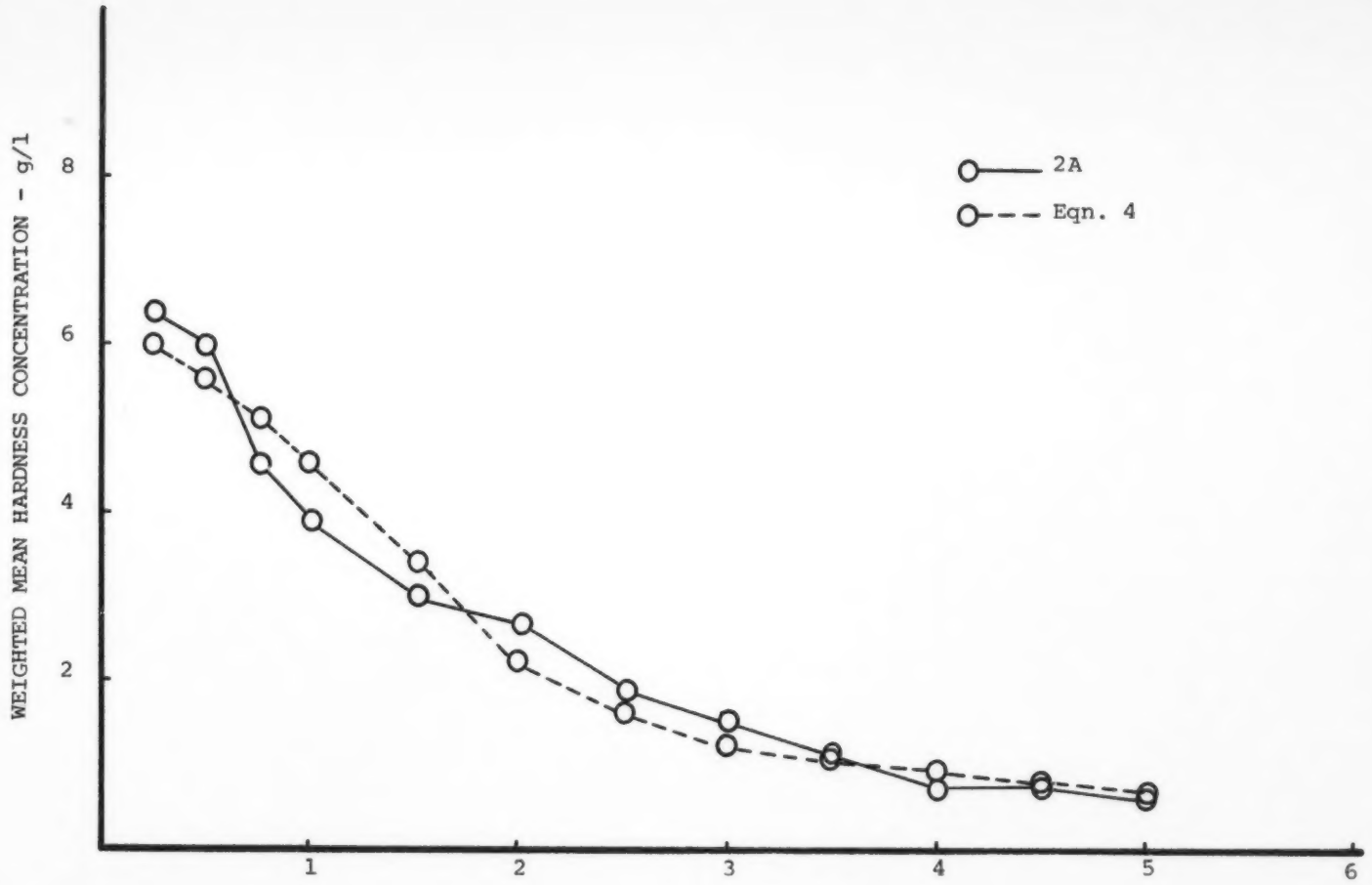


Figure 53. Hardness concentration comparison

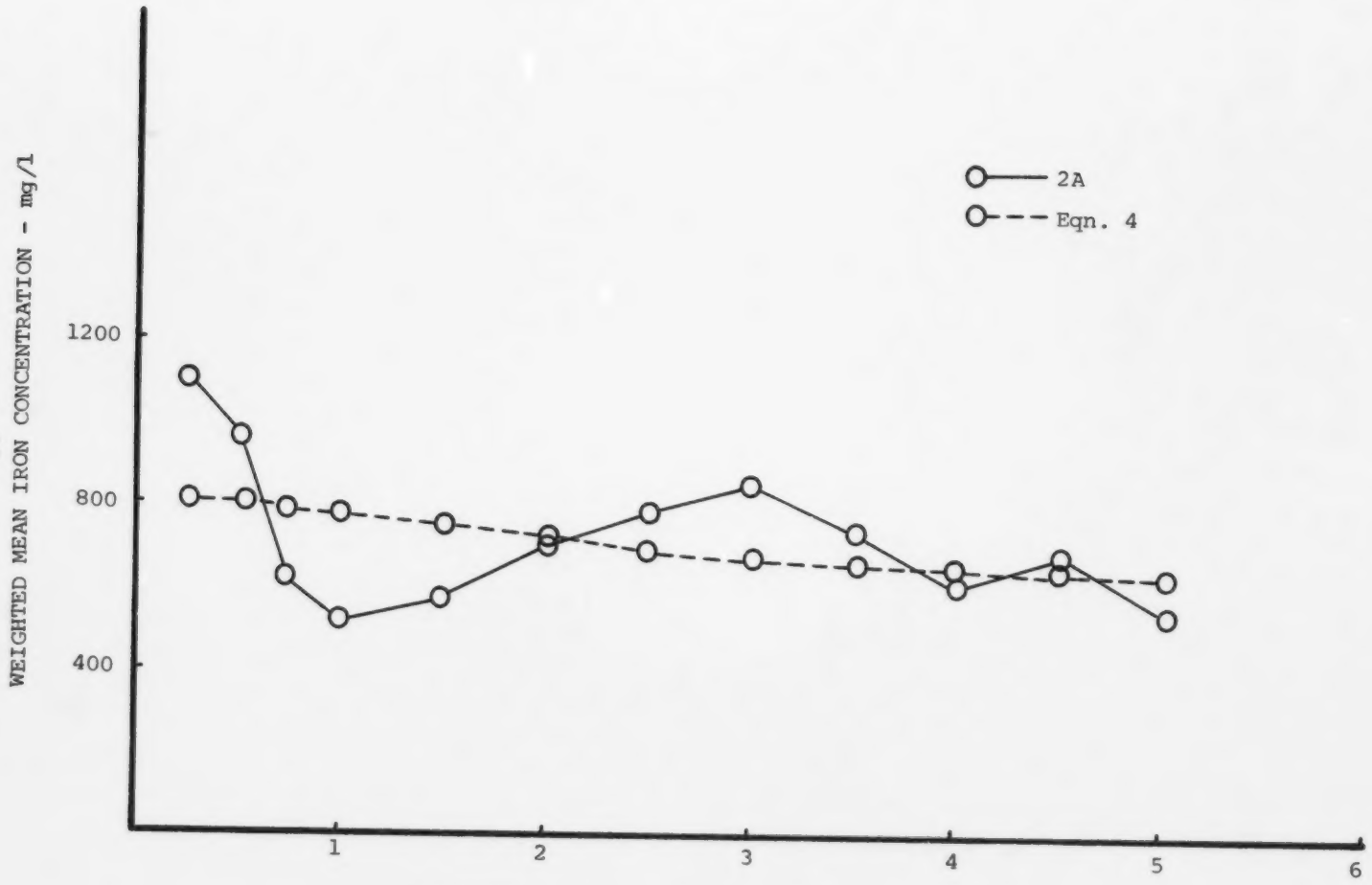


Figure 54. Iron concentration comparison

TABLE 20. EQUATION CONSTANTS

Parameter	Cell 2A			Cell 2B			Cell 2D			Cell 1		
	C_o	k	r[a]	C_o	k	r	C_o	k	r	C_o	k	r
COD	47930	.26	.98	54910	.25	.99	56560	.03	.90	42060	-.09	.95
Sulfate	816	.17	.95	1060	.13	.92	1110	-.07	.87	838	-.05	.99
Chloride	1950	0.0	.98	2350	-.08	.97	2150	-.07	.94	1380	-.01	.98
Hardness	6000	.23	.98	7650	.24	.99	6160	.20	.97	5840	.15	.99
Iron	804	.50	.34	886	.44	.60	1125	.38	.72	640	.33	.80

a. correlation coefficient

concentrations were highly erratic. To determine if the equation constants and the projected values might be sensitive to this initial weighted mean value this point was dropped from the least squares analysis. The results showed very little change in C_o, k or r from the least squares analysis that included the initial data point indicating little sensitivity to the initial erratic leachate concentrations from the onset of leaching to field capacity.

Mass Removal

Integrating the concentration times the flow rate over infinite time (Cqdt) yields a general expression for total leachable mass.

$$M = \frac{qC_o}{q/V - k} \qquad (5)$$

the total mass available estimated from this expression for 2A and 2B and the amount removed at a cumulative leachate volume of 4.5 1/kg of dry refuse are shown in Table 21.

TABLE 21. TOTAL ESTIMATED LEACHABLE MASS[a]

	Cell 2A		Cell 2B	
Parameter	Estimated[b] Total	Removal at 4.5 1/kg	Estimated[b] Total	Removal at 4.5 1/kg
COD	108	96.6	117	97.8
Sulfate	1.36	1.42	1.59	1.49
Chloride	2.19	2.46	2.28	2.24
Hardness	11.9	11.2	15.9	13.4
Iron	14.2	3.33	6.8	3.02

a. All values in g/kg of dry refuse

b. Equation 5

The accuracy of these total leachable mass projections is questionable since the estimate is derived from the least squares analysis of the data over an incomplete leaching history of the test cell. Residual analysis at closure of the cells indicated additional mass within the refuse. For example, residual chloride averaged 158 g/kg, more than 70 times the total amount projected to be available for leaching. Verification of Equation 5 and whether these large quantities remaining within the refuse will be leached at significant concentrations in the future would have to be determined by longer term testing or greater water throughput than was done with the Boone County cells.

Leachate Characteristics, Cell 1 Lower Pipe

One of the objectives of Cell 1 was to evaluate the leachate control effectiveness of the 46 cm silty clay liner placed in the base of the cell

(Figure 1). Less than 9,000 liters of leachate were collected from this pipe during the first 7½ years of the project, representing less than 1% of the total leachate collected. The total leachate quantity collected represented only one-third of the soil liner pore volume. Leachate samples were collected periodically from the lower pipe and analyzed for the same parameters as on the upper pipe samples.

In general, there were marked reductions in lower pipe leachate concentrations during the first half of the project. Table 22 shows the peak concentrations recorded in lower pipe leachate samples and the ratio to the peaks from samples in the upper pipe. Figure 55 depicts weighted mean total solids concentrations from both pipes over a 4 year period. The weighted mean total solids concentrations over this period were 7,540 mg/l for the lower pipe and 10,940 for the upper pipe leachate, a reduction of 31%. At the end of the project the total solids concentrations from both pipes were similar.

The pH of the lower pipe leachate was consistently higher during the first 4-5 years. After mid-1976 the trend was reversed and by the end of the project almost all the samples from the lower pipe had a lower pH. While iron concentrations in the early lower pipe samples were higher, possibly due to removal from the soil liner, removals as high as 80% were recorded after 8 years. Even at the end of the project approximately 40-50% of the iron was still being removed by passage through the soil. COD removals were as high as 90% during 1975 and thereafter declined slowly to 40-50%. Chloride and hardness removals were erratic in the first few years but ranged as high as 80% in some samples. By mid-1978 concentrations were about equal in the leachate from both pipes. In the final samples taken in August, 1980 chloride levels in the lower pipe were almost 3 times upper pipe concentrations and hardness was 902 mg/l in the lower pipe versus 592 in the upper pipe leachate.

Several factors preclude the use of the concentration change data in predicting leachate attenuation due to passage through a soil liner of similar thickness. Some of the leachate may have moved as far as 7.6 m laterally along the soil-synthetic liner interface after passage through the liner. Soil thickness also varied and was only about 5 cm at the collection gallery bulkhead. There was also a small hole or channel found during closure in the soil near the bulkhead, providing a direct hydraulic connection from upper to lower pipes. Evidence of leachate passage through this hole or the area of thin soil rather than uniformly through the entire liner is provided by the fact that total solids attenuation had all but ceased after collection of 9,000 liters of leachate, or only 1/3 of the soil pore volume. Whereas, in another study of this soil, attenuation of selected trace metals was evident for 5 or more pore volume exchanges[16]. Desorption of selected constituents from the soil such as hardness, chloride, calcium and sulfate were also occurring during the latter part of the project.

GAS ANALYSIS

Gas samples were taken at various locations and levels in all five test cells. Probe design is shown in Figure 6. For the first 8 months

TABLE 22. PEAK LEACHATE CONCENTRATIONS - CELL #1 LOWER PIPE

Parameter	Peak Concentration[a]	Ratio of Lower to Upper Pipe Peaks
COD	60,200	1.6
BOD_5	20,500	0.7
Kjeldahl-N	197	0.3
Ammonia-N	417	0.8
Orthophosphate	49	0.8
Sulfate	430	0.4
Alkalinity	5,420	0.6
Acidity	2,490	0.7
Conductivity	9,000	0.7
Total Solids	21,300	0.9
Sodium	825	0.8
Potassium	700	0.4
Chloride	1,020	0.6
Iron	480	0.8
Magnesium	266	0.7
Manganese	131	0.7
Calcium	1,560	0.7
Zinc	4.5	0.04
Hardness	5,030	0.7

a. Concentration in mg/l except for pH and conductivity (micromhos/cm)

samples were obtained from Cell 1 after pumping at a flow rate of 1130 cc/minute for 1 minute. Representative samples were not being obtained so the evacuation time was increased to 5 minutes after a study of sequential samples taken at 2, 3, 5 and 10 minute intervals. Gas samples from Cells 2A-2D were initially taken after 3 minutes of pumping at 33 cc/sec. This was eventually modified to 5 minutes of pumping to reduce residual oxygen. The sampling procedure was further modified by using a thermal conductivity detector to assure stable gas compositions were obtained before sampling. Analyses were done with a gas chromatograph for methane, carbon dioxide, and oxygen. Even with the careful sampling techniques results were quite erratic.

Typical carbon dioxide and methane content trends for Cells 1, 2B and 2D are shown in Figures 56 and 57. All cells showed rapid depletion of oxygen to less than 10% within a month in Cell 1 and to less than 4% within 2 weeks in Cells 2A-2D other than at level 1 in 2C. Oxygen levels generally remained less than 3% at most probe locations within the cells for the rest of the project. Occasional high readings of greater than 10% at selected points were probably due to sample contamination or probe failure. There did not appear to be any decrease in oxygen with depth. Oxygen within the soil cover in Cell 1 remained consistently less than 20% dropping to as low as 1% on one occasion.

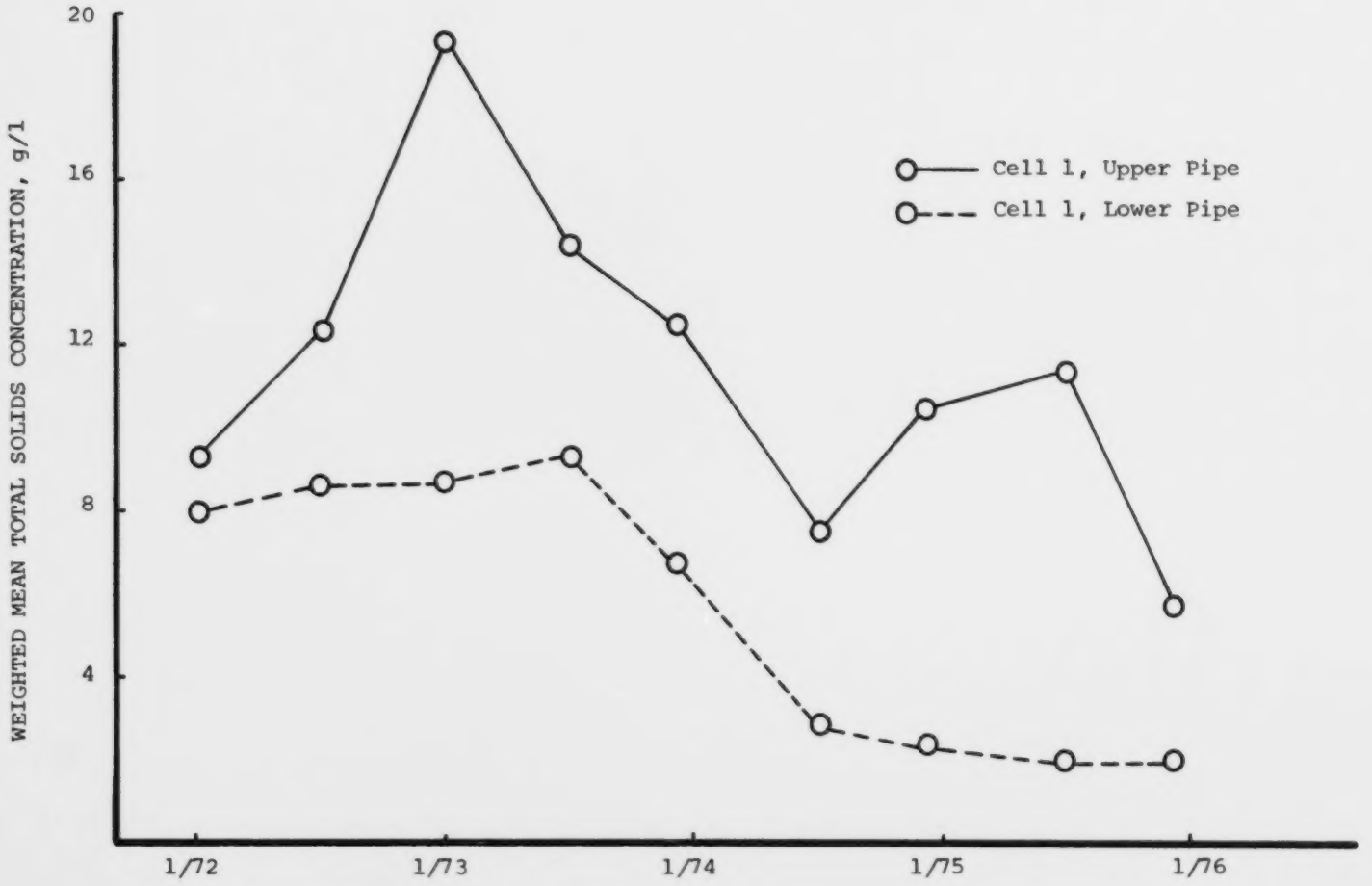


Figure 55. Cell #1, upper and lower pipe total solids concentration.

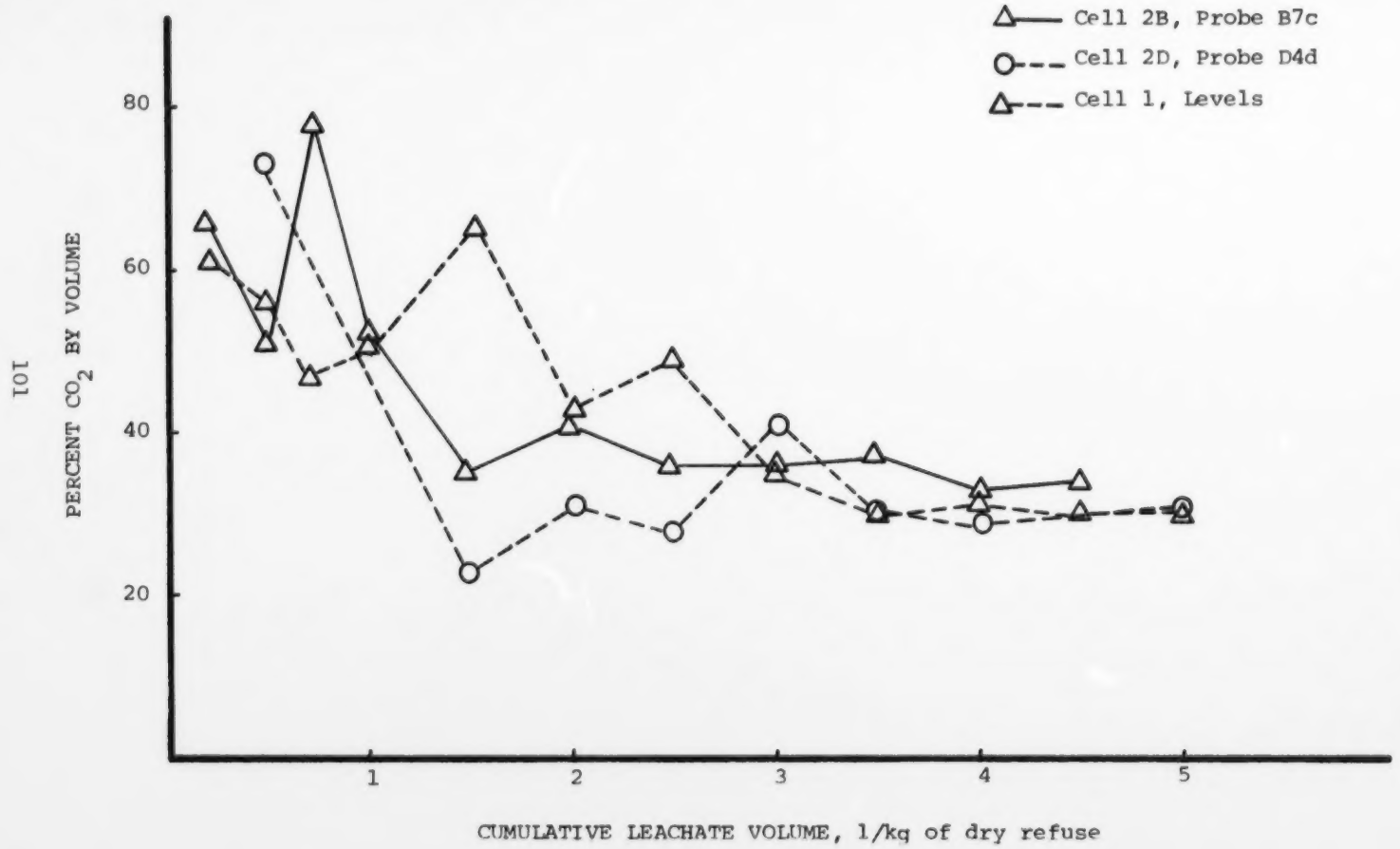


Figure 56. Carbon dioxide content - Cells 1, 2B, 2D

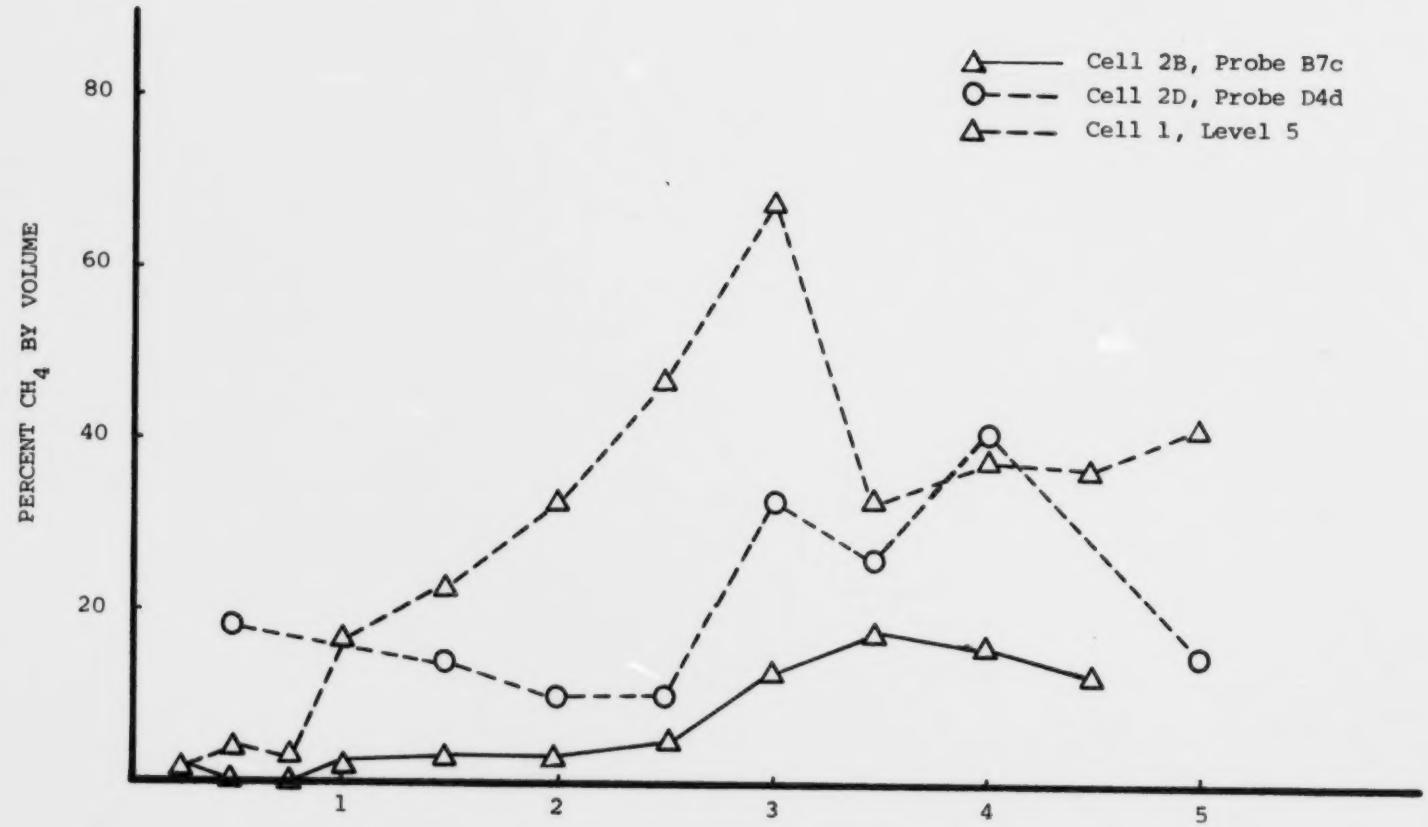


Figure 57. Methane content - Cells 1, 2B, 2D

The characteristic early carbon dioxide bloom appeared in all cells. Within 2 weeks after cell construction CO_2 levels reached as high as 45% in the center of Cell 1 and 38% in the center of Cell 2D. Levels in the small scale cells were slightly less. Peak levels of CO_2 were reached in all cells at about the time field capacity was achieved. Thereafter levels dropped slowly to 30-40% at the conclusion of the project. Trends and concentration levels in the small scale cells were similar. Carbon dioxide levels ranged from 5-20% higher by volume in Cell 2D than in the small scale cells for the first 3 years but were similar thereafter. CO_2 levels in the soil around Cell 1 remained at atmospheric levels until mid-1976 when 27% was recorded at probe W-4 located 6.1 meters from the refuse. This was immediately following a month of heavy rain which would have tended to block venting through the cell surface. High levels were again noted frequently during 1978-1980. A peak of 31% was recorded at probe W-7 in July of 1980.

Very little methane was detected until the cells reached field capacity. The earliest appearance of methane in Cell 1 was at the base of the cell and beneath the liner. Methane concentrations greater than 10% were not detected in the small scale cells until 2 years after similar levels were reached in Cell 2D. The rapid drop in methane in Cell 1 depicted in Figure 57 does not appear to be related to any sharp increase in oxygen or in leachate production. Only a slight decrease in leachate pH was apparent during this period. Methane as high as 45% by volume was detected in the soil probe W-7 located 6.1 meters from Cell 1 9 years after cell construction.

Methane production in the small scale cells was much slower than in 2D. Peak methane concentrations detected were 25% in 2A, 20% in 2B and 26% in 2C; concentrations were increasing with time. Although the results were erratic, methane levels recorded at levels 1 and 7 in the 3 small scale cells appear to be similar. Peak concentration recorded in Cell 2D was 57.9%. There did not appear to be any difference in methane volumes at levels 1 and 4. Probe D4b at the edge of the cell showed consistently less methane than D4d in the center of the cell until 1979 when it appears the concentrations began to be somewhat greater. There was little similarity between the methane history in 2D and in the small scale cells, 2A-2C.

TEMPERATURE

Thermocouples and thermistors were placed at various locations in the five test cells as shown in Figures 4, 8, 9, 10 and Table 3. Typical probe design is shown in Figure 6. Wire leads were protected by polyethelene tubing. Additional sensors were placed in the soil at various depths around the cells.

No early peak temperatures were recorded from Cell 1 due to instrumentation problems. Peaks recorded in Cells 2A-2D are listed in Table 23. Temperatures as high as 124°F were recorded at level 1 in Cells 2A and 2B. Peaks declined with depth in the small scale cells but were similar at the 3 levels in Cell 2D.

Temperature variation with depth is shown in Figures 58 and 59 in which the annual minimum and maximum temperatures are plotted for Cells 2A

TABLE 23. PEAK REFUSE TEMPERATURES, CELLS 2A-2D

Probe	Peak Temperature Recorded[a]	Date
2A1c	124	8-18-72
2B1c	124	8-18-72
2B1e	98	8-17-72
2C1c	99	8-17-72
2D1a	95	8-19-72
2D1b	118	8-19-72
2D1c	122	8-18-72
2D1d	114	8-19-72
2A4c	102	8-15-72
2B4c	98	8-14-72
2B4e	94	8-17-72
2C4c	96	8-16-72
2D4a	101	8-18-72
2D4b	121	8-18-72
2D4c	121	8-17-72
2D4d	119	8-17-72
2A7c	96	8-14-72
2B7c	85	8-14-72
2B7e	75	8-14-72
2C7c	91	8-15-72
2D7a	82	8-17-72
2D7b	113	8-16-72
2D7c	115	8-16-72
2D7d	117	8-16-72

a. degrees Fahrenheit

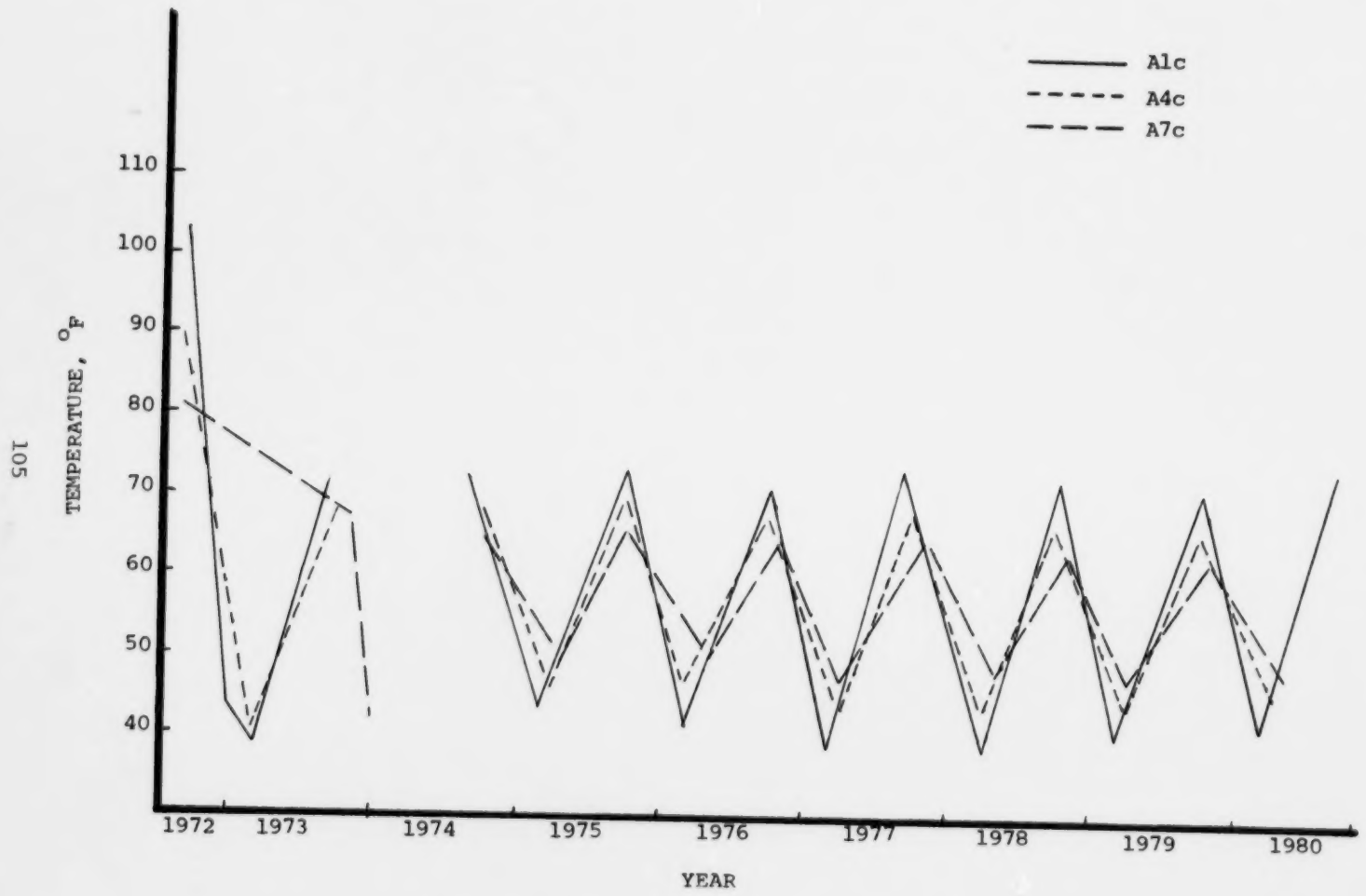


Figure 58. Annual temperature range: Cell 2A

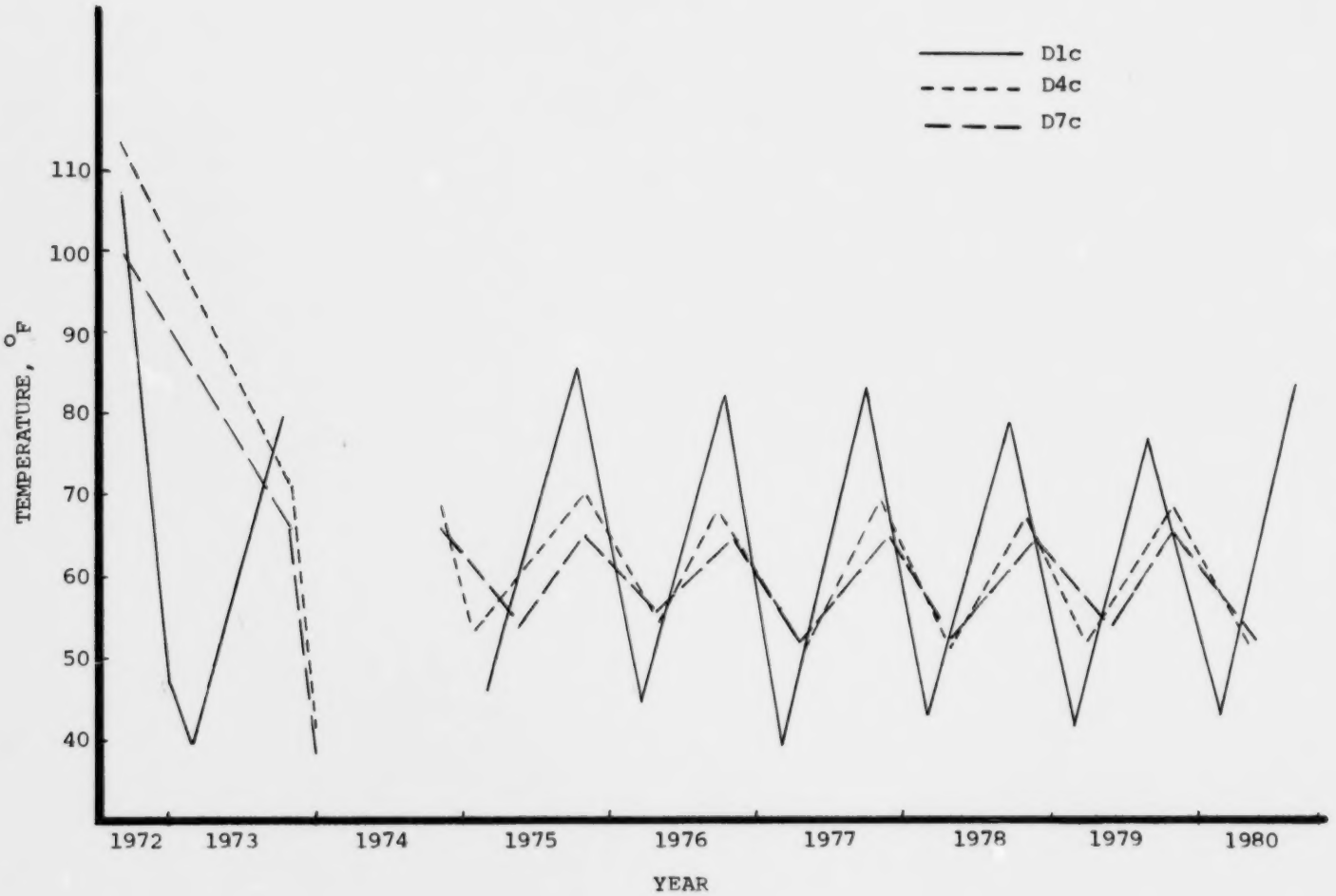


Figure 59. Annual temperature range: Cell 2D

and 2D. The pattern of decreasing amplitude with greater depth was consistent for all cells. There was also a time lag of 1-2 months from when the annual high or low was recorded near the base of the cell and when they were recorded at level 1 near the surface. Annual high temperatures in 2D exceeded those in 2A, 2B and 2C at level 1 (Figure 60). The lows were not substantially different. This difference in peaks indicated greater seasonal aerobic activity in 2D or possibly some heating effect due to the covering. The extent of difference in peaks was not noted at levels 4 and 7 (Figure 61). The covers used for 2A, 2B and 2C were dome shaped and provided approximately .6 m of air space above the gravel, whereas they polymeric membrane used to cover 2D was placed directly on the gravel. This lack of insulating air space is considered the likely cause of the temperature difference.

Figure 62 shows the difference in annual peaks recorded in the center (D4c) and near the edge (D4a) of Cell 2D. A lateral thermal gradient of 4-5^{o}F was caused by soil cooling along the side during the winter and early spring. This same gradient existed not only during low temperature periods but also when seasonal highs were recorded in Cell 2B, but only at level 4.

After about 1½ years soil and refuse temperatures at similar depths were generally within a few degrees indicating the end of active aerobic decomposition. Except near the surface of Cell 1, lower annual temperatures were recorded in the soil and the highs were about the same in both the refuse and the soil. There was also a time lag between soil and refuse peaks. This amplitude difference and time lag was thought to be due to specific heat differences and perhaps remaining aerobic activity within the refuse.

SETTLEMENT

Settlement readings were taken periodically on all test cells. Cumulative settlement as a percent of total refuse depth is shown in Figure 63. For Cell 2D the settlement is the average elevation of 9 points on the cell surface subtracted from the initial average elevation. Corrections have been made for cell surface disturbance and regrading during 1977. Bench marks referenced to the settlement markers in Cell 1 were destroyed so only estimates of the settlement can be made.

Settlement in the small scale cells was quite similar with over half the total recorded during the first fourteen months following cell construction. Final settlement in these cells ranged from 15.2-2.17.1% of total cell refuse depth. Settlement over the surface of 2D averaged only 10.6% of refuse depth, probably due to the 30% higher initial in-place refuse density than in 2A-2C. Estimated total settlement at the deepest point in Cell 1 was 12% of the refuse depth. The initial refuse density in Cell 1 was 35% higher than that in 2A-2C.

Settlement monuments placed on the surface of the refuse and on the soil cover in Cell 1 showed wide variations. Seasonal cover soil expansion was considerable. For future studies it would be advisable to place the base of any monument on the refuse below the soil cover, preferably to a depth greater than frost penetration.

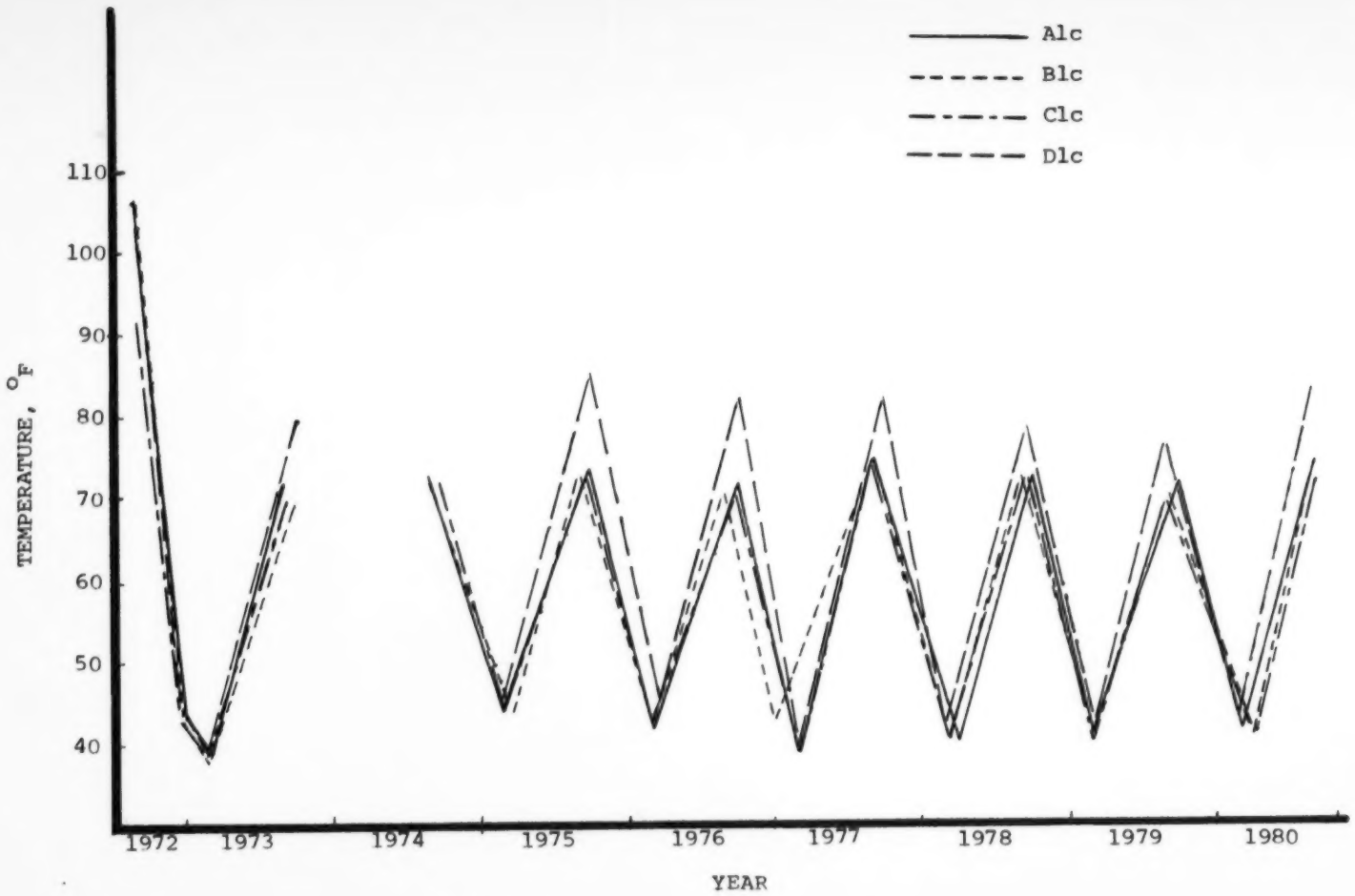


Figure 60. Annual temperature range: Cells 2A-2D, Level 1

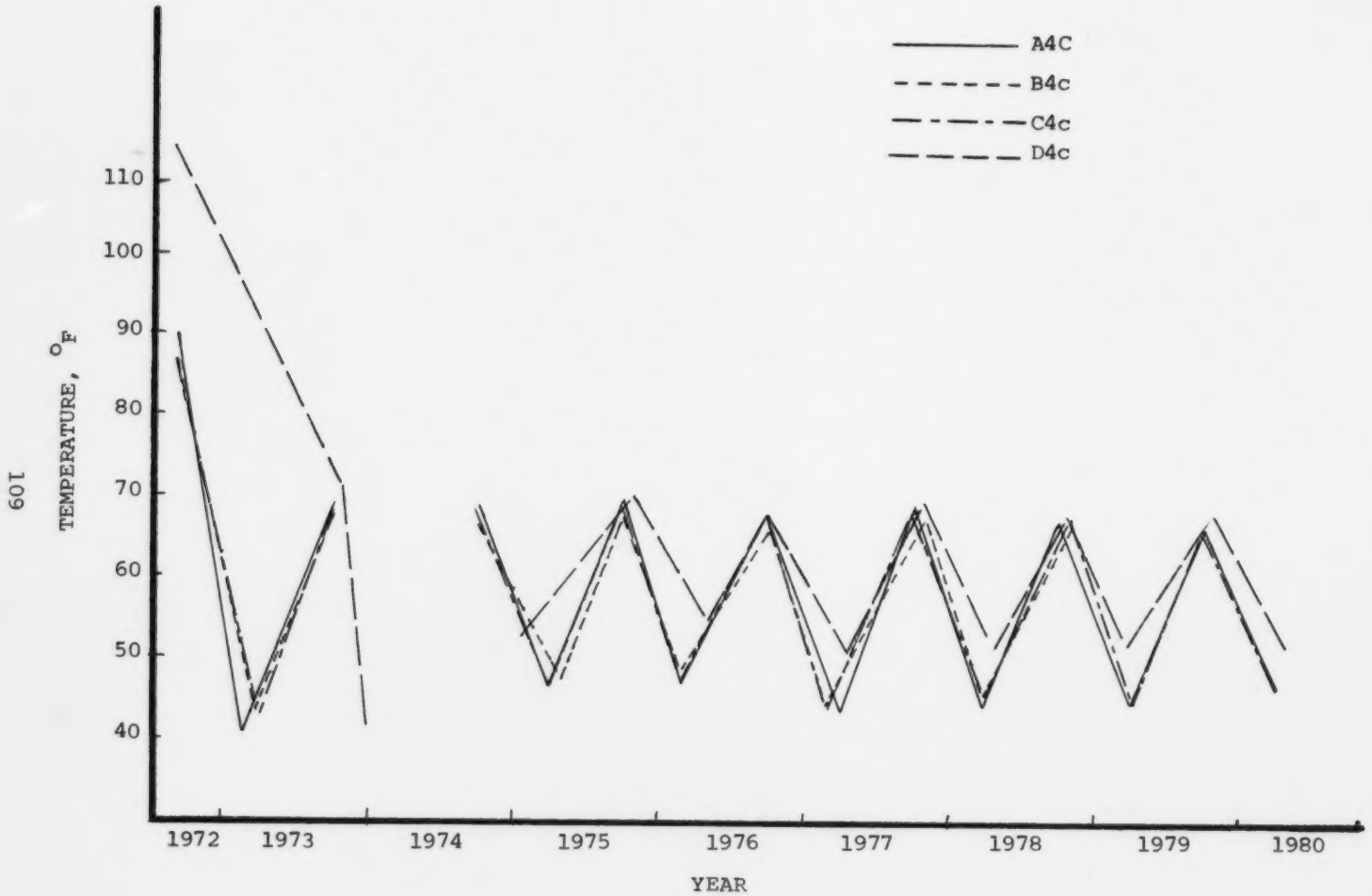


Figure 61. Annual temperature range: Cells 2A-2D, Level 4

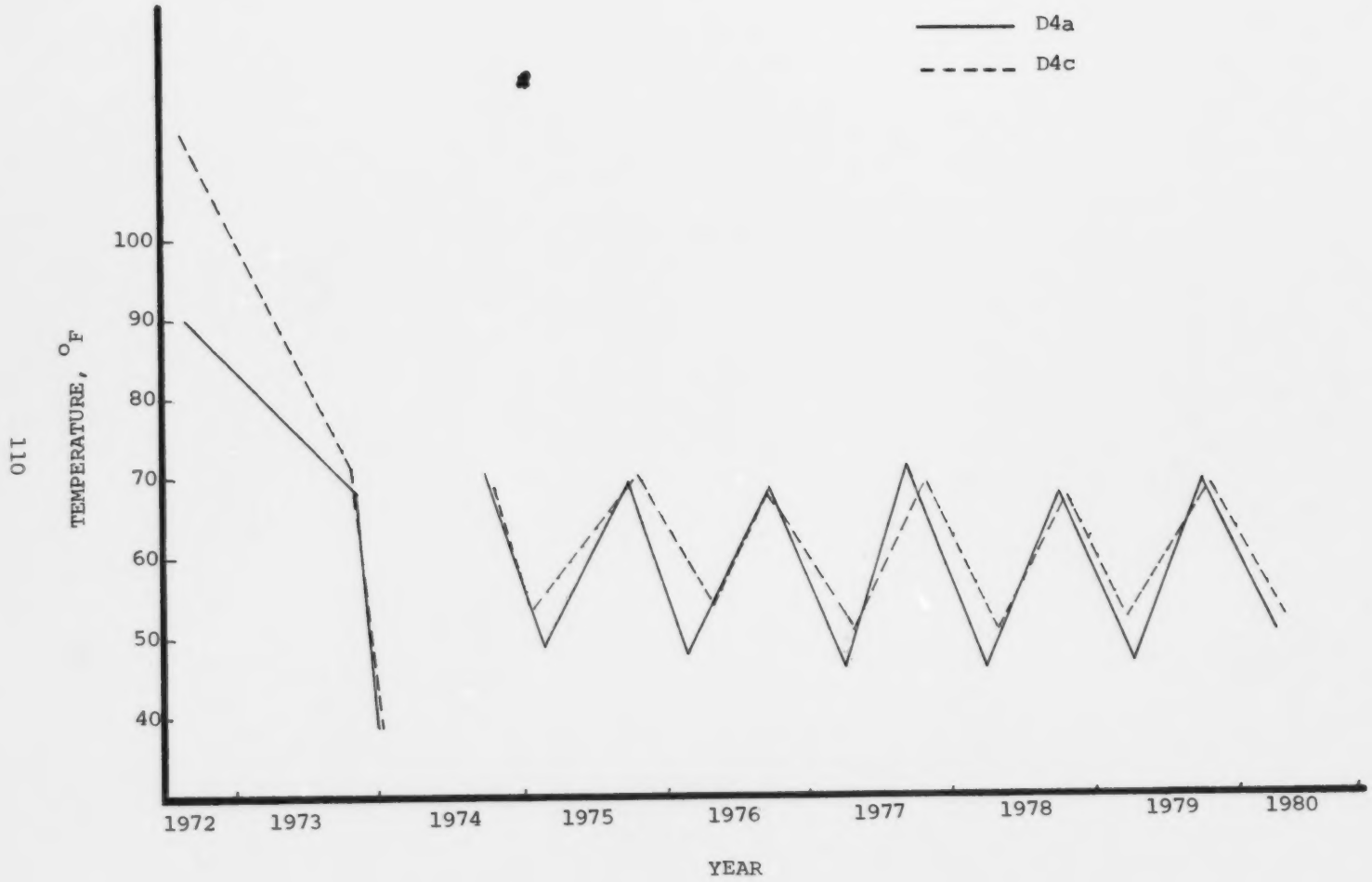


Figure 62. Annual temperature range: Cell 2D, Level 4

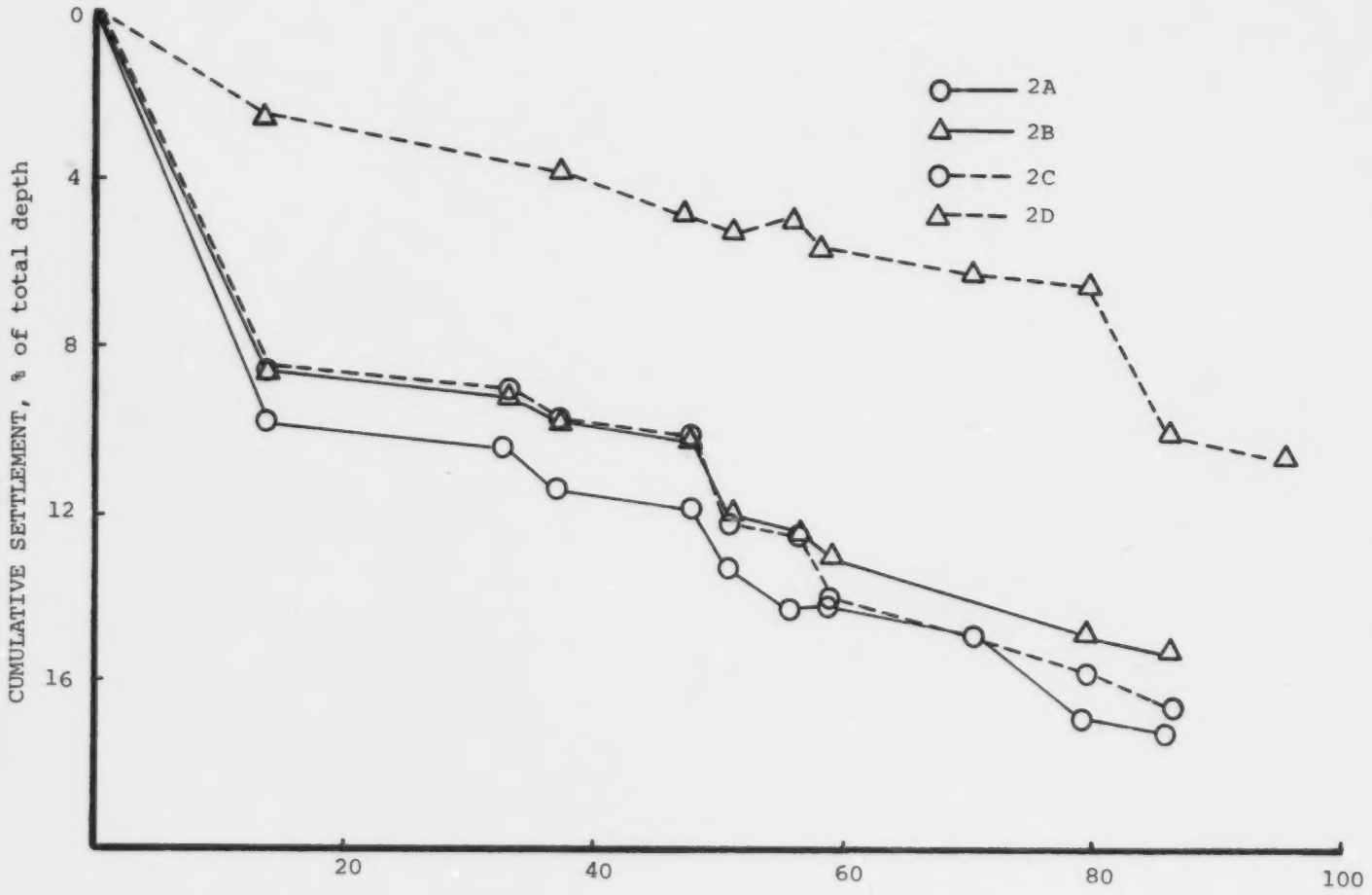


Figure 63. Settlement, cells 2A-2D

COMPARISON OF PERFORMANCE OF TEST CELLS

One of the primary objectives of the research was to evaluate the behavior of a field-scale test cell, 2D, as compared to similarly constructed small-scale cells. It was desired to determine whether scaling factors were involved or if the small cells produced duplicate results so that future research efforts might utilize small, less expensive cells for prediction of field behavior.

The experimental design was to have similar initial refuse composition, moisture, and density in all cells and to control water input to approximately 500 mm per year. Composition and initial moisture content were found to be statistically similar and refuse depths varied only 5%. The in-place wet refuse density in 2D was 45% greater than the average refuse density in the small cells.

Water input, infiltration, and evaporation were controlled by periodically covering the cells and with a layer of pea gravel over the soil cover. Leachate collected (Figures 14 and 15) from cell 2C was so substantially different from 2A and 2B that the leachate data was not used in any comparative analysis. Leachate production from 2D was much larger than from the remaining small-scale cells, 2A and 2B, and was in excess of precipitation. By the end of the project, almost twice the leachate per unit of collection surface area had been produced in 2D than 2A and 2B. This excess leachate production and the ponded water outside the liner indicate the possibility of significant diluting leakage into 2D from the sides.

Only minor differences in temperature, settlement and gas composition were noted when comparing the performance of the small scale cells. Temperatures were essentially the same in Cell 2D as in the small cells except for some surficial heating due to the cover over 2D. Settlement in the large cell was only 2/3 of that in the small cells, perhaps due to the initial 45% greater wet refuse density. There was a substantial difference in methane gas found in the cells, with delayed production and lower concentrations in the small-scale cells 2A-2C as compared to 2D.

Leachate concentration trends in 2D were not unlike those in the small-scale cells, but typically the magnitude of peak concentrations and mass removals were lower, quite possibly due to the diluting sidewall leakage. Since it appeared that this leakage could have passed through a portion of the refuse, corrections to the concentration data based simply on excess water could not be made. This large difference in leachate production from 2D is probably sufficient to preclude comparability of cell performance based on leachate characteristics.

To compare leachate concentration histories the Chow test[17] for stability of coefficients was chosen. As used here this test essentially compares the least squares fit of two linear equations best describing the data from two individual cells, such as 2A and 2B, with the fit of a single equation developed from the combined set of data from the cells. The F statistic calculated from a ratio of the residual sum of the squares of the

linear equations describing the data is used as the measure of statistical comparability.

Actual concentrations rather than the weighted means were used in the analysis. Since Equation 4, a simple exponential, had shown good correlation with the weighted mean concentration trends, the log transform of the equation was used for the necessary linear equations and least squares fitting. The resultant equation coefficients for the comparison of cell concentration histories are compiled in Table 24. C_o is the concentration at field capacity, the starting point of data comparison, k is the mass transfer coefficient and r is the linear correlation coefficient for the log equation. F is the test statistic value for comparison of the least squares equations independently describing 2A and 2B and the equation describing the combined data.

The tabular F at the .05 level for the degrees of freedom for the combined 2A and 2B data set is 3.0. Therefore only 3 of the parameters, chloride, manganese, and zinc had similar concentration histories based on a comparison of least squares semi-log equations. A comparison of 2A and 2D showed similarity for magnesium only.

Therefore while graphical comparison of the weighted mean leachate concentration histories indicated general performance similarity, statistical comparison indicated only marginal uniformity in the actual leachate data from cells 2A and 2B. Typically most of this difference was in higher peak concentrations recorded from 2B. Gas concentrations, temperature, settlement and the weighted mean leachate concentration similarities, when viewed together, indicate that the two identical cells generally performed in a similar manner.

The difference in initial in-place density of 2D and the volume of leachate as compared to 2A and 2B probably precluded performance similarity of this field scale cell with the smaller cells. The data, particularly gas, settlement, and leachate concentrations all indicated that the field scale cell did perform differently than the small-scale cells. Since the cell was constructed differently (density) and had significant leakage it cannot be concluded that small-scale cells would not be adequate models of large cells that were constructed and operated similarly. However, the problems in operating 2D similarly to the small cells are probably indicative of only part of the differences that might be encountered in an actual field situation. Variables such as soil cover types and quantities, more heterogeneous waste types and non-uniform infiltration through the refuse could all be expected, making it doubtful that a few controlled small-scale cell experiments could provide accurate predictions of actual landfill behavior.

TABLE 24. EQUATION COEFFICIENTS, 2A-2B COMPARISON

Parameter	Cell 2A			Cell 2B			Cells 2A and 2B			
	Co[a]	k[b]	r[c]	Co	k	r	Co	k	r	F[d]
Total Solids	19,600	.27	.932	26,200	.22	.962	22,500	.25	.936	18.6
COD	39,300	.30	.929	49,400	.24	.954	44,000	.27	.935	17.8
Kjeldahl N	1,080	.13	.962	1,580	.06	.977	1,310	.09	.962	14.4
Ammonia N	812	.12	.958	1,170	.07	.974	974	.09	.957	11.9
Chloride	1,560	-.01	.923	2,090	-.10	.940	1,800	-.05	.929	3.0
Potassium	1,260	.02	.979	1,740	-.05	.986	1,470	-.02	.976	17.6
Hardness	4,940	.26	.948	7,350	.22	.927	6,000	.24	.907	16.1
Calcium	1,570	.26	.941	2,160	.25	.874	1,840	.26	.879	10.1
Magnesium	335	-.13	.850	506	-.14	.840	415	-.15	.806	6.7
Iron	630	.56	.234	690	.49	.262	661	--	.012	10.6
Manganese	29	.27	.807	39	.16	.808	33	.22	.796	2.9
Zinc	102	-.16	.816	168	-.05	.952	130	-.11	.826	.99

a. C_o - concentration at field capacity, t = o

b. k = mass transfer coefficient in Equation 4, $C = C_o e^{-(q/v - k)t}$

c. r - linear correlation coefficient

d. F - test statistic

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Appendix 1. SITE LAYOUT